POTENTIAL USE OF HYDROGEN AS A DEFENSE LOGISTICS FUEL

REVISION 1

REPORT DES41M1

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LMI
GOVERNMENT CONSULTING

NOVEMBER 2004

LMI

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DES41M1, REVISION 1/NOVEMBER 2004

Executive Summary

In response to a provision within the National Defense Authorization Act for fiscal year 2004, the Defense Logistics Agency's Defense Energy Support Center (DLA DESC) contracted with LMI to examine the potential use of hydrogen as a defense logistics fuel. Congress directed DLA to assess the feasibility of substituting hydrogen fuel and fuel cell technology, in both transportation and power generation applications, domestically and overseas; the potential for reducing air emissions; and the implications for the cost and footprint of military operations.

To frame a response to those requirements, we formulated three key questions:

- Is the use of hydrogen a viable option for DoD?
- What infrastructure development would be necessary, and what timeline would be expected, to begin using hydrogen fuel in step with industry developments?
- What would be the costs and benefits of making the transition to a hydrogen fuel-based force, for both a home-based force and a deployed warfighting force?

Our investigation of these issues involved reviewing literature in detail and conducting interviews and personal communications with industry leaders and DoD personnel with subject matter expertise.

The first step in our approach to these issues was to profile energy usage within the U.S. and specifically within DoD. We then examined many of the developments and goals established for introducing hydrogen on a wider scale, revealing the many barriers and opportunities related to hydrogen introduction. Next we looked at ongoing research and development that seeks to overcome those barriers and exploit the opportunities offered by the technology. Some of these barriers, from a DoD perspective, are daunting—with some of the rewards being equally significant. We also explored the impact of bringing some of this technology to DoD, and specifically to the battlefield.

That assessment has allowed us to draw these conclusions, in response to the questions we posed:

- Hydrogen may be a viable fuel for future DoD use in 10–30 years. Its use would bring a number of operational benefits and environmental improvements worthy of continued exploration. Some applications in small-scale power generation and body-portable devices offer the best opportunity over the next 10–30 years. Without a major technological development, however, the use of hydrogen as a mobility fuel in major weapon systems is not feasible for the next 30–40 years.

- Infrastructure requirements and development issues are still evolving. A decision to produce hydrogen fuel cell vehicles for commercial sale is not expected until at least 2015. Much of the size, design, complexity, and cost of the new infrastructure cannot be determined until several developments and decisions take place in the private sector regarding how hydrogen will be produced, distributed, and stored. DoD should not make decisions before the private sector establishes its course. As a consequence, infrastructure-related programming is not necessary before POM-10.

- The costs and benefits of transitioning to hydrogen are extremely difficult to gauge and cannot be done with accuracy at this time. The technology offers some potential operational advantages to the warfighter: stealth, sustainment, and multiple sources of fuel. If renewable energy is used for generating hydrogen, then a significant reduction in greenhouse gases may be achievable. But before these benefits can be realized, significant technical challenges and infrastructure costs must be successfully confronted.

On the basis of our findings, we make these recommendations for introducing hydrogen as a DoD logistics fuel:

- *Develop and manage a DoD strategy and roadmap for the introduction of hydrogen.* The first element of this recommendation is to create an oversight and collaboration structure. Once in place, use that structure to develop a comprehensive, integrated strategy and plan for introducing hydrogen within DoD. With both of these pieces in place, then consider the process for financial planning and programming for introducing hydrogen and its related infrastructure, and identify roles and responsibilities.

- *Continue engagement with industry and government stakeholders.* Keep well informed and involved in hydrogen and alternative fuels-related developments. Work to continue, expand, and develop partnerships with other government entities and industry.

- *Consider weapon system implications.* Keeping in mind that the introduction of hydrogen in major weapons systems is decades away, incorporate energy planning into acquisition planning. Seek out near-term trials and opportunities to explore and demonstrate the introduction of the technology.

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Chapter 1
Introduction

PURPOSE

In response to a provision in the National Defense Authorization Act for fiscal year 2004, the Defense Logistics Agency's Defense Energy Support Center (DLA DESC) contracted with LMI to examine the potential use of hydrogen as a defense logistics fuel. This study responds specifically to the following language in the Act:

> The committee directs the Defense Logistics Agency to examine and report to the committee no later than one year after the date of enactment of this Act on the potential use of hydrogen as a defense logistics fuel. The report should include an examination of potential applications of hydrogen by the military as a transportation fuel and for power generation; potential sources of hydrogen fuel for military use domestically and overseas; potential reductions in the cost and footprint of deployment for military operations that use hydrogen fuel and fuel cell technology; and potential reductions in air emissions from military operations that use hydrogen fuel and fuel cell technology.[1]

This study seeks to determine the potential for hydrogen to become a fuel in applications within DoD that use petroleum-based products. Our report is intended to provide objective and useful information to Congress on the state of hydrogen technology development, as well as recommendations on the future of hydrogen use in DoD.

The LMI study team researched the feasibility of substituting hydrogen fuel and fuel cell technology in each of the following categories (stated in the National Defense Authorization Act of 2004), while considering the potential reduction in air emissions and in the cost and footprint of deployment in military operations:

- Transportation
- Power generation
- Other military uses, domestically and overseas.

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[1] 108th Congress 1st Session Senate Report No. 108-46, *National Defense Authorization Act for Fiscal Year 2004*, May 2003.

This study considers many aspects of the use of hydrogen as an energy source for DoD. Specifically, we consider three key questions:

- Is the use of hydrogen a viable option for DoD?
- What infrastructure development would be necessary, and what timeline would be expected, to begin using hydrogen fuel in step with industry developments?
- What would be the costs and benefits of making the transition to a hydrogen fuel-based force, for both a home-based force and a deployed war-fighting force?

Hydrogen technology is applicable to a variety of types of energy consumption. For example, hydrogen fuel cells can be used as a replacement for batteries, or to replace petroleum-fueled internal combustion engines in vehicles. Essentially, hydrogen technology is being developed to provide the energy that many applications currently require. This report, however, responds specifically to the congressional request to research a specific dimension of the challenge—using hydrogen in applications that use petroleum-based products within DoD.

STUDY APPROACH

LMI assembled an expert team in response to the specific needs of this project to conduct a thorough qualitative study to meet the stated goals. Phase I of the project began with a detailed literature search for applicable information on hydrogen and fuel cell technology and deployment. We searched government and industry sources and Web sites, as well as journals and other publications available on the topic. In conducting the research for the report, we reviewed and compiled over 175 information sources. Based on this literature review, we formed a preliminary assessment to determine what further information and validation was needed to support the study. Phase II of the project was comprised of completing the literature review and conducting interviews with government and industry leaders who are involved in the hydrogen transition process. We interviewed, either in person or via telephone, many of the experts and change agents in the field of hydrogen and fuel cell technology. We coupled the outcomes of our research with our experience in the energy field to formulate our findings and recommendations. Phase III of the study consisted of a preliminary review of our results by DoD stakeholders and generation of the final report.

Project Team Organization

Program Director: Mr. Steven J. Stone, P.E., DEE, CIH. Mr. Stone was responsible for the overall performance of this project to ensure that we met the needs and expectations of DESC and complied with LMI's ISO 9000 certified quality management process. Mr. Stone is a registered professional engineer and a former Army officer.

Program Manager: Mr. Stuart Funk. Mr. Funk managed all aspects of the study and served as the primary point of contact with the DESC contracting officer's technical representative (COTR), ensuring that the products met DESC's goals and professional expectations. He conducted detailed research, including in-depth reviews of existing literature, reports, and periodicals. In addition, Mr. Funk traveled to San Antonio, Texas, to conduct a site visit of the Missile Fuels (DESC-M) Commodity Business Unit (CBU), which has the responsibility for purchasing gases and other chemicals for DoD. Mr. Funk was a career Naval officer with over 15 years experience in DoD energy logistics.

DoD/Energy Logistics Team: Mr. Marc McConahy. Mr. McConahy provided in-depth research on the current state of DoD fuel use and technology. He also traveled to San Antonio to meet with DESC-M leadership and to California for meetings with industry leaders and government officials. His experience as a member of a Presidential Task Force on alternative fuels provided support to the LMI research team's knowledge base. As a retired Naval officer, he has years of petroleum management experience coupled with background in alternative fuels technology and deployment issues.

Hydrogen Technology and Industry Team: Mr. David Haberman and Mr. Thomas Gross. These team members researched the state of hydrogen technology development supported by industry and government. They traveled to California to discuss hydrogen technology status, plans, issues, and expectations. Mr. Haberman has served on several senior executive panels and has been engaged on hydrogen transition issues for many years. Mr. Gross recently completed a federal service career with Department of Energy (DOE), most recently managing programs supporting advanced vehicle technologies and alternative fuels.

Study Support: Mr. Sonny Oh, Dr. Michael Canes, and Ms. Lisa Powell. Mr. Oh and Ms. Powell were responsible for providing data collection, analysis, and overall support to the final report. Mr. Oh focused on DoD energy and cost data analysis, report writing, and data analysis presentation. Mr. Oh utilized his military (USAF Reserve) and energy management backgrounds to provide valuable insight into DoD energy use. Ms. Powell assisted in research and report preparation. Dr. Canes, former Vice President and Chief Economist for the American Petroleum Institute, provided senior level technical and economic review of the briefings and final report.

Report Structure

Each of the four subsequent chapters in this report presents a major element of our study.

CHAPTER 2: DoD ENERGY USE ANALYSIS

Analyzing the potential use of hydrogen in DoD requires an understanding of DoD's current and historical energy use. Through collecting and analyzing recent energy data, we explore the trends and patterns of DoD's energy use. We characterize the types of fuel used and present this data relative to overall federal energy use. We present data on energy use within the United States and overseas, and distinguish between the amounts required for facilities and mobility applications. Evaluating current energy use helps to better understand what portion of overall DoD energy consumption has the highest potential to be replaced by hydrogen.

We discuss current DoD mandates in energy development and management that may impact the development of hydrogen as a fuel. We present some information on DoD transformation that may influence DoD's use of hydrogen. The significance of DoD in the energy market is characterized as well.

CHAPTER 3: HYDROGEN DEVELOPMENT

Current research and development of hydrogen-related technologies, by both industry and government, reveals opportunities for future use of hydrogen in DoD. Our investigation of commercial development of hydrogen technology provides background essential for the further analysis and discussion of incorporating hydrogen into DoD applications.

In this section of the report we discuss current public- and private-sector hydrogen development activities. We examine the goals and objectives of current projects and their projected impacts on hydrogen costs, environmental quality, and technical feasibility. We also consider the time frames anticipated for achieving hydrogen development program goals.

CHAPTER 4: DoD HYDROGEN LOGISTICS AND APPLICATIONS

Understanding the benefits, costs, and vulnerabilities of the current fuels used by DoD is another important step. In determining whether and when DoD may make the transition to hydrogen, it is necessary to compare the logistics considerations related to both hydrogen and petroleum. We evaluate the differences between hydrogen and petroleum logistics and investigate the potential applications and risks of transitioning to hydrogen. We discuss domestic, overseas, and battlespace logistics for DoD hydrogen use. We analyze the costs and benefits of implementing hydrogen technology in DoD.

CHAPTER 5: FINDINGS AND RECOMMENDATIONS

The final portion of the report consists of recommendations for DoD. Through researching and discussing current fuel use in DoD, current hydrogen development, and the potential costs and benefits of using hydrogen, we arrive at determinations about the viability of the hydrogen option. We propose a timeline for

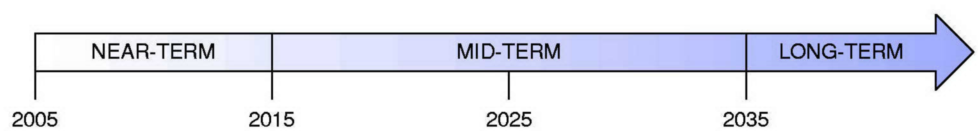
future decisions on implementing hydrogen technologies and infrastructures. We also discuss the complexities and limitations of developing recommendations on this subject.

Report Terms

This report may use some uncommon terminology and it is described for purposes of clarity:

- Energy chain—describes an end-to-end process to deliver energy from a source to the point of use (also referred to as "well-to-wheels").
- Body-ported power—small-scale power (usually < 2 kW) that can be transported and managed at the individual war fighter level.
- Reforming—the process of producing pure hydrogen from compounds containing hydrogen (i.e., natural gas or fossil fuels).
- Timing—the terms "near-term" (next 10 years), "mid-term" (10-30 years), and "long-term" (over 30 years out) characterizing the chronological scale of trends or developments (illustrated in Figure 1-1).

Figure 1-1. Hydrogen Technology Timeline



THE HYDROGEN TRANSITION

The context of this study must consider the overall national and international direction of the use of hydrogen as a fuel. If developed nations make the transition to hydrogen as a major energy source, replacing petroleum, it will be critical that DoD be prepared to adapt to the change. The enormous capital cost of infrastructure and the timing of decisions on research, development, and deployment will require additional study.

In his 2003 State of the Union Address, President George Bush stated,

> A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy.

The President seeks a national commitment to develop hydrogen technology. We are engaged in a search for alternative fuel sources because our nation faces a variety of problems associated with the extraction, production, and use of petroleum and petroleum products. We seek energy solutions in response to challenges associated with global warming, reliance on foreign sources of oil, potential oil shortages, and vulnerability to acts of terrorism.

In response to such problems, scientists and policy makers are researching the potential of transitioning to a "hydrogen economy." As the nation begins to shift to hydrogen fuel technology, we may encounter significant technological, sociological, and economic challenges. However, the national commitment to pursuing a hydrogen economy will support us, as we address and overcome concerns and barriers encountered along the way. DoD will face many of the challenges confronted by civilian institutions, but will encounter additional challenges that are unique to the military. DoD must seek to minimize potential risk, while maximizing the benefits to its mission.[2]

Though a variety of technological and sociological challenges are associated with hydrogen, its possible benefits are substantial. Hydrogen offers the potential for greater energy efficiency, a reduction in greenhouse gases, increased use of renewable sources of fuel, increased energy security, greater national security, and improvements in air quality. This report discusses these challenges and benefits, with consideration of the needs of DoD and the goals of the National Defense Authorization Act.

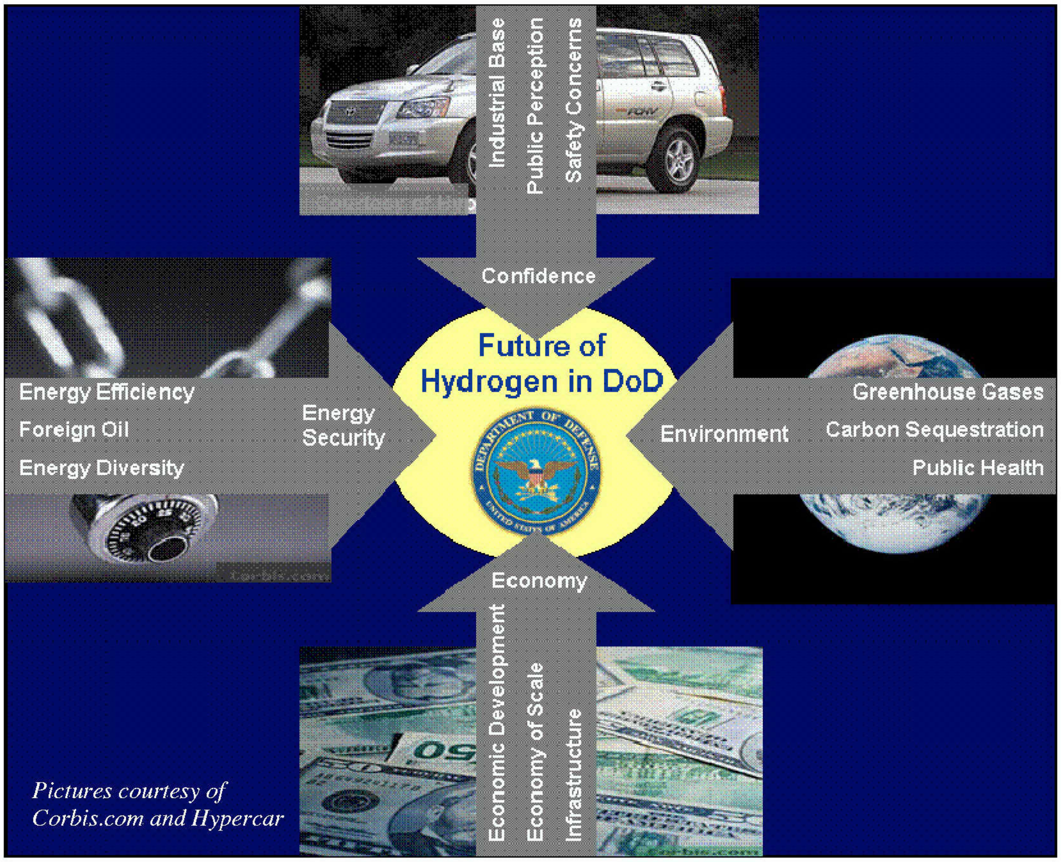
> *HYDROGEN BASICS*
>
> *Hydrogen is the most simple, most plentiful element on our planet. It is estimated that hydrogen makes up 75% of the mass of the universe. At first glance of these facts, one may assume hydrogen fuel is abundant; however, the term "hydrogen fuel" is a bit of a misnomer. Unlike oil and natural gas, hydrogen is not a primary source of fuel. It is a secondary source of energy because hydrogen atoms do not exist alone in nature. Hydrogen must be produced from an existing resource using another energy source, such as natural gas or solar power. Peter Hoffman provides a clear illustration in his book on hydrogen technology, "We might compare hydrogen to the transmission in an automobile: It does not generate power by itself, but it makes it convenient to convert the power available from an engine into useful work."*[2]

The subject of transitioning to a hydrogen economy is associated with a variety of perspectives and issues. Though we understand many of the arguments for and against hydrogen, we are committed to presenting an unbiased report on the subject. In this report, our objective is to present the available facts, and provide analysis based on the information reviewed.

Figure 1-2 depicts the various perceptions and issues confronting more widespread introduction of hydrogen within DoD. All these factors (both positive and negative) will have an influence on the outcome. We have grouped these factors into four components: economy, environment, energy security, and confidence.

[2] Hoffman, Peter. Tomorrow's Energy: *Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet*, MIT Press, Cambridge, Massachusetts, 2001.

Figure 1-2. Issues Influencing the Future of Hydrogen in DoD



Economy

Making a transition from traditional fuel sources to hydrogen will require a variety of expenditures on the part of DoD. These include the cost of hydrogen (raw materials and the production process) and the infrastructure necessary to produce, store, and distribute it. Any discussion of the potential for hydrogen in DoD must consider these costs. Arriving at detailed projections of costs, given the remaining development work on hydrogen technologies, is extremely difficult. However, we will note the findings and projections of other studies.

Environment

One of the reasons that our nation and the world are considering the use of hydrogen is that it promises a host of potential environmental benefits. Global warming is becoming an area of concern for scientists, policy makers, and the general public. Hydrogen can be produced and used with no climate-changing emissions. However, these benefits depend on a variety of factors. Since there are so many unknowns regarding the path that hydrogen technology and implementation will take, it is difficult to be certain whether a transition to hydrogen will bring environmental benefits.

Energy Security

It is possible that a DoD transition to hydrogen fuel could enhance energy security. A major area of concern has been our reliance on foreign sources of fuel. If we decrease our need for petroleum, we could increase our independence. Additionally, it is also a possibility that creating a more diverse energy supply could make us less vulnerable, especially in operations. We must consider the security issues of introducing a new technology that directly impacts the success of DoD's missions.

Hydrogen can bring significant capabilities to the DoD mission. By combining hydrogen in the right systems and technologies there is potential to achieve:

- *Near silent operations*
- *Significantly reduced infrared exposure*
- *Longer power availability than batteries*
- *Lighter weight than batteries*
- *Extraction of hydrogen from suitable feedstocks nearly anywhere at any time.*

These capabilities would be highly valued in many military missions. However, it will be imperative to carefully select which form of hydrogen is needed for a specific application, as the physical state is an essential determinant of how hydrogen is produced, transported, and stored.

Confidence

A transition to hydrogen in the civilian and military sectors will require a significant level of consumer confidence. Since development in the private sector appears to be leading the way, we may have to see the confidence in the private world reach acceptable levels before the technology prevails. Since hydrogen use for energy production is relatively novel at this time, many consumers have limited exposure to the technology. It is very likely that consumers will be most concerned with the safety of hydrogen.

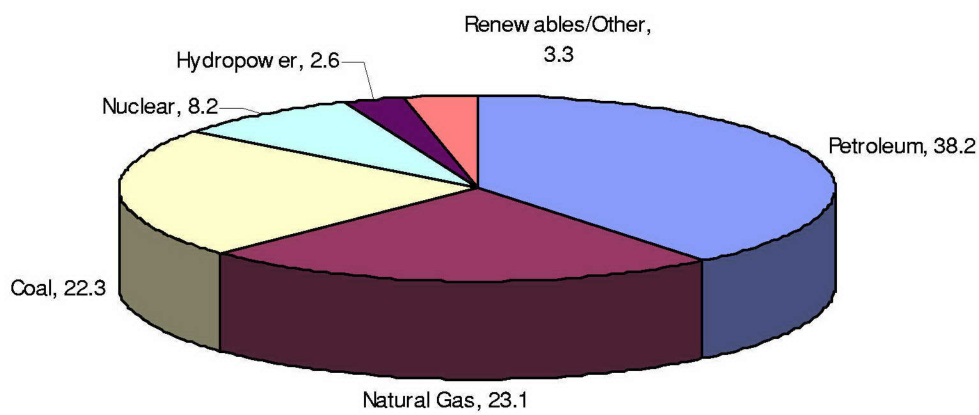
Chapter 2
DoD Energy Use Analysis

To fully appreciate the opportunities and barriers for hydrogen as the future fuel of choice for DoD, we must first understand energy usage profiles within the U.S. and specifically within DoD. This chapter describes the current trends and patterns of energy consumption for the U.S. and the DoD communities.

U.S. ENERGY CONSUMPTION

Total world energy consumption in 2001 was 403.3 quadrillion British thermal units (Btu).[1] The U.S. DOE estimates the total primary energy consumption in the U.S. was 97.7 quadrillion Btu in 2002. Thus U.S. consumption represents about one-quarter of the total world energy consumption. Figure 2-1 illustrates a breakout of the total U.S. energy consumption in 2002 by type of energy source.

Figure 2-1. U.S. Energy Consumption by Energy Type, 2002 (Quadrillion British Thermal Units)

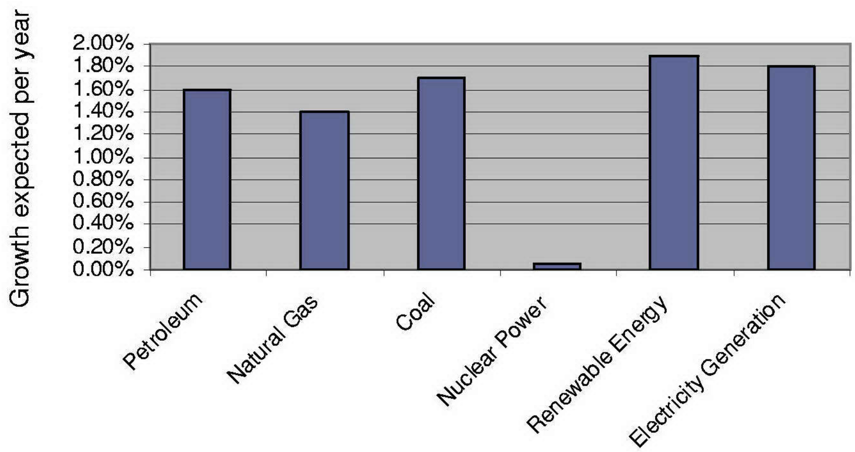


According to forecasts in the DOE Annual Energy Outlook 2004 with Projections to 2025, total energy consumption in the U.S. is expected to increase by an average of 1.5 percent per year over the next two decades.

[1] The International Energy Agency's Key Word Energy Statistics 2003, page 37, reports the world total energy consumption at 10165.03 million tons of oil equivalent (Mtoe). The conversion calculation is (1 Mtoe = 3.968 × 10 + E7) equals 403.3 quadrillion Btu. (One quadrillion is 1 × 10 + E15.) This consumption figure includes energy sources such as coal, crude oil, petroleum products, natural gas, nuclear, hydroelectric power, combustible waste, geothermal, solar, and wind.

Figure 2-2 illustrates different growth rates predicted by DOE for the energy types. Growing demand for electricity is likely to be met by building power generation sources using more natural gas, coal, and renewable energy.

Figure 2-2. DOE Forecast of U.S. Energy Growth Rates



Source: DOE/EIA-0383, *Annual Energy Outlook 2004 with Projections to 2025*, January 2004.

DoD Energy Consumption Profiles

In FY01[2], the total U.S. federal government consumed 0.6 quadrillion Btu of primary energy sources, of which DoD consumed 0.4 quadrillion. Primary energy used by the federal government and DoD represent, respectively, only 0.6 percent and 0.4 percent of total U.S. energy use (97.7 quadrillion Btu). These numbers include energy used to operate all DoD-owned facilities, auxiliary equipment, and weapons platforms. Nuclear power generated for Navy ships and submarines are not included in this figure.

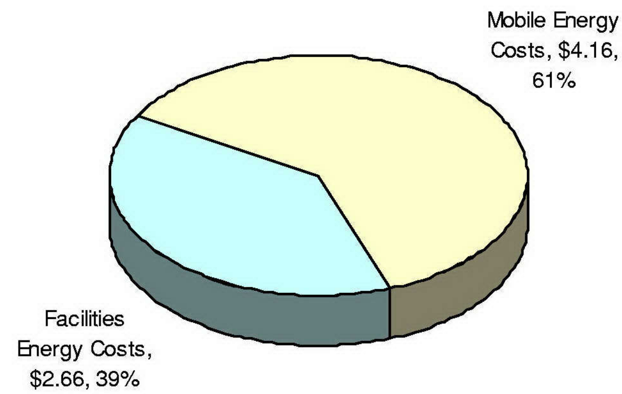
Although DoD's energy use may seem insignificant in relation to the nation as a whole, its consumption equates to approximately a $6.8 billion expenditure, and represents about 1.8 percent of DoD's annual appropriations.[3] Figure 2-3 illustrates a breakout of DoD total energy expenditures in FY03—$2.66 billion for facility energy and $4.16 billion for mobile energy.[4]

[2] FY02 data by DOE/Federal Energy Management Program (FEMP) were not available at the time of report preparation. Based on historical trends, the annual change rate is less than 0.2 percent.

[3] The Budget for Fiscal Year 2005, Historical Table, OMB Report, $388.9 Billion appropriation for Defense-Military.

[4] DoD Energy Consumption Report prepared for DOE/FEMP Annual Report to Congress.

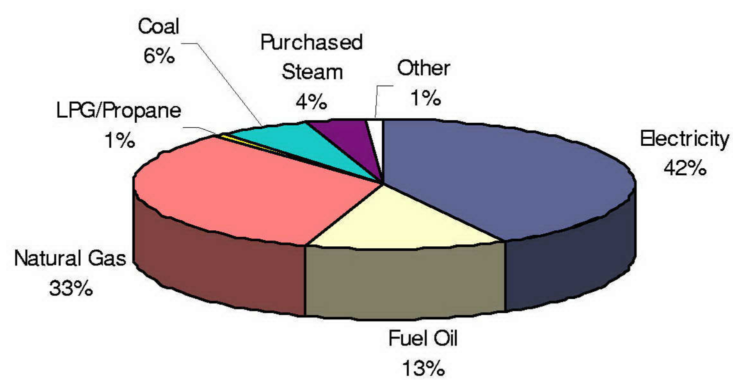
Figure 2-3. DoD Energy Expenditure of Facility and Mobile Energy, FY03 (Billions of U.S. Dollars)



DoD Facility Energy Consumption

Figure 2-4 shows a distribution of FY03 DoD facility energy consumption by fuel types. Although electricity represented 42 percent of total facility energy usage, it accounted for 70 percent of the total cost at $1.8 billion. Most DoD installations rely on a local power grid network to meet all of their electricity needs.

Figure 2-4. Distribution of DoD Facility Energy Use (Consumption), FY03



Natural gas, fuel oil, and purchased steam are used primarily for comfort heating purposes by DoD installations. Small shares of these fuel sources are used to produce hot water and other industrial applications. Few DoD installations operate coal-fired electric power plants.

Most fuel oil DoD purchased was used to power central heating plants that utilize circulating high-pressure steam, low-pressure steam, and hot water technologies. Using fuel oil for heating purposes still remains an economically competitive option despite the drawbacks of emission considerations and environmental liability from possible contamination from fuel storage tank leakage. DoD prefers to use

natural gas for heating rather than fuel oil. It maintains fuel oil as an option of dual capability to capitalize on fluctuating natural gas prices.

DoD Mobile Energy Consumption

Mobile energy is defined as fuel used to power DoD weapons platforms, tactical equipment, and all types of vehicles. Unlike facility energy, the vast majority of mobile energy depends on petroleum-based products.

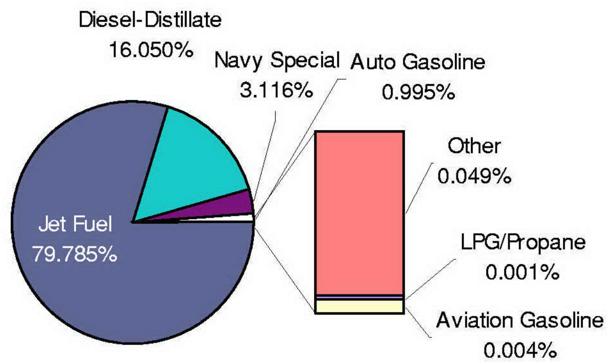
Table 2-1 provides total FY03 consumption and annual expenditures for mobile energy by fuel type.

Table 2-1. FY03 DoD Mobile Energy Consumption

Fuel types	Annual consumption (millions of gallons)	Annual cost ($ millions)
Auto gasoline	48.9	41.6
Diesel-distillate	789.0	653.5
LPG/propane	0.06	0.05
Aviation gasoline	0.2	0.2
Jet fuel	3,922.2	3,336.5
Navy special	153.7	124.9
Other	2.4	2.6
Totals	4,916.46	4,159.35

Figure 2-5 shows the share of mobile energy (in terms of Btu) consumed by various uses. JP-8 and JP-5 jet fuels are the dominant fuels used for flying operations and for the Army's heavy armored vehicles. DoD's use of gasoline and distillates for ground transportation vehicles and maritime use represents 17 percent of total mobile energy usage. Engine technologies for these vehicles are developed in private industry and share the same technological innovations that arise in the commercial sector. DoD's consumption of alternative fuels through experiments and pilot projects is minimal.

Figure 2-5. DoD Mobile Energy Use (Consumption), FY03

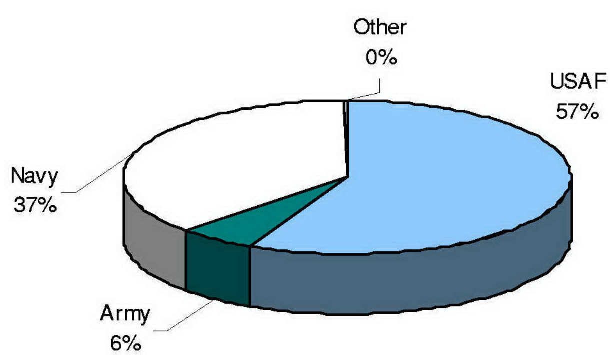


Although DoD relies on private industry to develop these weapons platforms, energy selection choices are largely driven by the performance of systems and logistical impacts.

Mobile Energy Use by the Military Services

Figure 2-6 illustrates shares of mobile energy consumption by the three military services and other DoD agencies. The U.S. Air Force consumes the most energy, largely owing to its use of aviation fuel.

Figure 2-6. Mobile Energy Use by Military Services and DoD Agencies, FY03

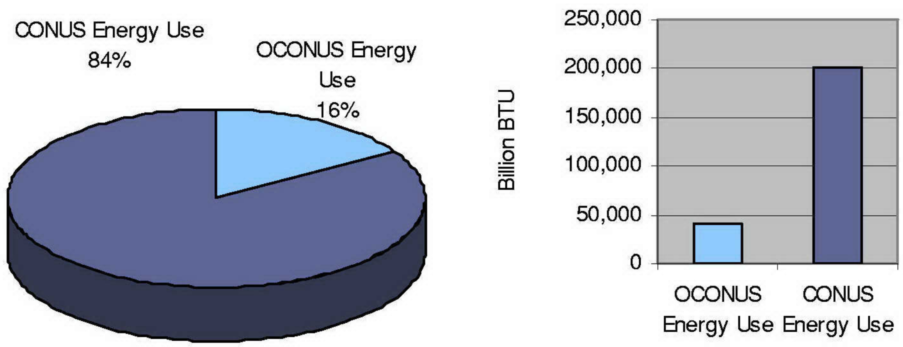


Overseas DoD Facility Energy Use

Overseas facility energy consumption represents 16 percent of total DoD facility energy consumption (Figure 2-7). Similar breakouts for mobile energy consumption are not available.[5] Overseas DoD installations rely on host nation utility companies to supply electricity and natural gas.

[5] Defining overseas versus domestic consumption for mobile weapon systems and platforms would require guesswork and arbitrary estimates that would produce unreliable results.

Figure 2-7. CONUS versus DoD OCONUS Facility Energy Consumption, FY03

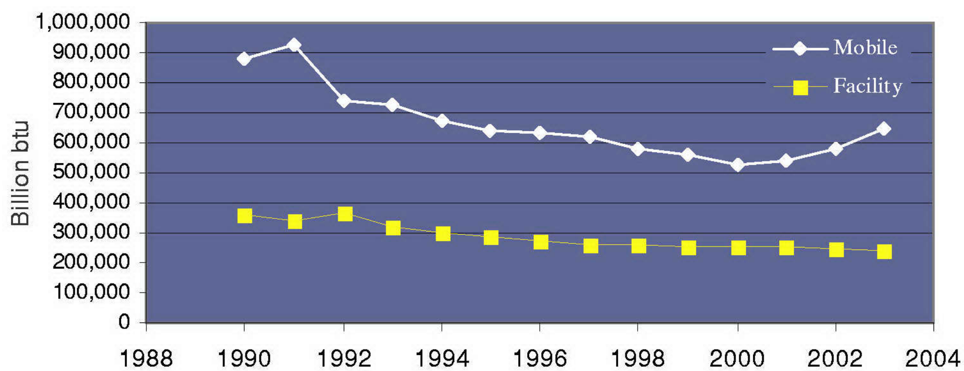


DoD Energy Use in Peacetime versus War

It is important to differentiate energy use during major conflict from consumption during times of peace. Figure 2-8 shows variations in consumption for facility and mobile energy use reflecting high tempo operations conducted during time of war.

The trend of steadily dropping facility energy consumption reflects a reduction of facilities, the gradual force drawdown after the Cold War, and Base Realignment and Closure (BRAC) actions. In contrast, mobile energy use shows increasing consumption during the first Gulf war (Operations Desert Shield and Desert Storm), Operation Iraqi Freedom (OIF) and the global war on terrorism. Aside from those spikes, general mobile energy consumption reflects a gradual draw-down of weapon systems after the end of the Cold War.

Figure 2-8. DoD Energy Use During War and Peace



DoD Facility Energy Use Reduction Directives and Initiatives

Since the energy crisis in the early 1970s, DoD installations have been directed to conserve energy and increase facility energy efficiency. The National Energy Conservation Policy Act (NECPA) mandated federal agencies to track energy use

(measured in Btu per square foot of facility space). These earlier provisions were revised and inserted into the Energy Policy Act of 1992, which established energy reduction goals for federal agencies. Again, similar provisions are currently being introduced in the proposed energy bills in the Senate (S. 14) and House of Representative (H.R. 6).

The Energy Policy Act of 1992 required federal agencies to reduce energy use by 20 percent (measured in Btu/ft^2) by 2000, using the 1985 consumption as the baseline. Building on this legislation, Executive Order 13123 mandated a 35 percent reduction in facility energy use by 2010, using the 1985 baseline. DoD has invested \$1.5 billion[6] of direct appropriations in energy retrofit projects to improve energy efficiency and to minimize waste. Also, DoD has used third-party financing to improve energy efficiency where the initial capital improvement costs are amortized with the energy savings. In FY01 alone, DoD awarded \$228 million worth of energy retrofit projects using the third-party financing mechanism. Through sustained investments in energy conservation efforts, DoD so far has achieved 25 percent of energy reduction compared to the 1985 consumption baseline.

Since the 1970s, numerous more energy-efficient technologies have been introduced and marketed for lighting, heating, air conditioning, induction motors, appliances, and digital equipment. These have gradually replaced older, more obsolete technologies used for similar applications. For example, today's T-8 electronic ballast fluorescent lights are over 40 percent energy efficient and produce higher quality lighting than traditional light bulbs. Similar advances have been made for heating and air conditioning systems and appliances. Through concerted, organization-wide, programmatic efforts, many of these technologies have been selectively implemented in DoD facilities.

Implications of Future Force Structure Change on DoD Facility Energy Use

As DoD redeploys troops stationed in Germany and South Korea, the facilities supporting these forces will most likely be closed and turned over to the host nations. CONUS installations that receive these returning forces will have to expand their existing infrastructure. Although the overseas facilities will close, facilities almost as large will have to be built at CONUS installations, which might offset energy reductions at the overseas installations.

Future Forecast for DoD Mobile Energy Use

DoD continues to decommission Cold War-era weapon systems and replace them with often more efficient and more capable platforms, so less petroleum energy may be required to operate them. For example, the Air Force plans to retire

[6] 2001 Annual Report to Congress on Federal Government Energy Management and Conservation Program Fiscal Year 2001, February 4, 2004. \$1.5 billion is calculated as 2001 constant dollars.

current F-15s and F-16s and replace them with much more capable but smaller numbers of F-22 and Joint Strike Fighter (JSF) aircraft. The Air Force accomplishing future missions with fewer tactical fighters could potentially reduce JP-8 fuel consumption.

The U.S. Army is also developing lighter but more agile combat capabilities in its Future Combat Systems. Heavy armored vehicles such as M-1 tanks and Bradley units are being replaced with lighter, less fuel consuming Strykers. This trend toward fielding lighter platforms will most likely reduce overall fuel consumption.

The U.S. Navy is considering reducing the number of ships and forward-stationing them to shorten travel times between CONUS homeports and overseas deployment areas. These strategic trends may result in reducing the Navy's fuel consumption.

Although the future operational tempo of these systems will affect the amount of fuel consumed, it is difficult to forecast that usage at the present time.

DoD Impact on Energy Markets

DoD is the largest single energy user in the United States, with annual energy expenditures of $6.8 billion to operate its facilities and supply fuel to mobile units. Although this annual outlay represents significant purchasing power, DoD's annual usage represents only 0.4 percent of annual U.S. energy consumption. Because DoD organizations are scattered around the globe, its attempt to consolidate its purchasing power by bundling individual installation needs have been successful for petroleum and to a lesser extent for electricity and natural gas.

Installation energy purchases have been affected by physical infrastructure requirements, regulatory mandates, and a market structure that prevent DoD from purchasing aggregate or bundled supplies. For example, DoD cannot purchase electricity at lower cost in the Southeastern states and transfer it to installations in higher cost areas such as California.

DoD organizations are totally dependent on the private sector to produce and supply most of its energy needs. Although DoD is a large consumer of energy, it does not have sufficient buying power to influence the underlying market forces affecting the energy industries throughout the entire nation. To maximize its purchasing power, DoD has to make energy system choices and meet its basic fuel requirements based on what is already available in the marketplace.

Petroleum Market

DoD mobile energy needs are met with primarily petroleum-based fuel. In 2003, DoD purchased 4.9 billion gallons of petroleum-based fuel to operate facilities and mobile platforms. The annual DoD petroleum consumption represents 0.32 million barrel equivalent per day. Given that world oil demand in 2001 was

75.3 million barrels per day and that the U.S. consumed about one-quarter of the world total at 19.6 million barrels per day, DoD's consumption accounted for 0.4 percent of world consumption and 1.6 percent of U.S. consumption.[7] The average DoD purchase price of petroleum-based fuel during FY03 was $0.85 per gallon. Given the cost competitiveness of petroleum and lack of suitable alternatives for engines burning non-petroleum fuel, DoD will continue to rely on petroleum-based fuel to operate its mobile platforms for many years.

U.S. dependence on imported oil has grown over the past decade as domestic oil production has declined. This trend is expected to continue. DOE estimates that net imports of oil (which accounted for 54 percent of total U.S. petroleum demand in 2002, 42 percent in 1990, and 37 percent in 1980) are expected to reach 70 percent of total U.S. petroleum demand by 2025. Given the U.S. increasing dependence on imported oil, potential supply disruptions could have financial and operational consequences for DoD.

Natural Gas Market

Natural gas is the preferred fuel source for comfort heating at DoD facilities, since it is more environmentally benign and poses fewer of the logistical problems associated with transporting fuel oil. In FY02, DoD consumed 77 billion cubic feet of natural gas. Given that DOE estimates that the U.S. consumed 22.8 trillion cubic feet of natural gas in 2002, the DoD share represents 0.3 percent of national consumption. The DoD impact on the U.S. natural gas market with a 0.3 percent market share is negligible.

The natural gas market has been deregulated since the early 1990s, and in recent years natural gas prices have been prone to wild fluctuations. Recent price volatility has forced DoD installations to better manage potential risks from spikes in spot market prices triggered by chronic supply shortages. DoD installations are encouraged to maintain fuel oil as an emergency backup fuel and hedge against possible supply disruption. In addition, many DoD organizations have used the DESC to bundle their requirements in order to negotiate more competitive prices and secure a more reliable supply.

Recent natural gas prices have remained at levels substantially higher than those of the 1990s. This high price has led to a reevaluation of expectations of future trends in natural gas markets, the economics of exploration and production, and the size of the natural gas reserves. As demand for natural gas grows, DOE is projecting greater dependence on imports of LNG. To accommodate the additional demand, the industry will push for expansion of existing terminals and development of new facilities. DOE projects that the total demand for natural gas will increase at an average rate of 1.4 percent per year. Increasing the use of natural gas for electricity generation and industrial applications accounts for most of the projected demand growth.

[7] British Petroleum BP Statistical Review of World Energy June 2002.

Electricity Market

A reliable supply of electricity from local power grids is vital for sustaining DoD operations. Without consistent electricity, DoD installations cannot function. Although backup emergency power generation capabilities exist, their outputs are insufficient to sustain operations other than the most critical activities.

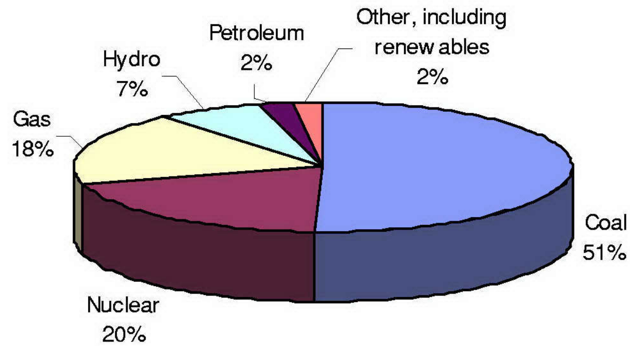
Lighting fixtures, induction motors, and electronic equipment exclusively require electricity to function. All lighting technologies such as incandescent, fluorescent, and high-intensity discharge lighting require electrical power. Induction motors convert electrical power into mechanical energy needed for industrial production lines, heating and cooling systems, pumps, elevators, and other equipment. Electronic equipment based on semiconductors and integrated circuits, including computers, require electricity as the power source.

In FY02, DoD consumed 30 billion kilowatt hours of electricity. Given that the DOE estimate of total electricity consumption in 2002, including purchases from electric power producers and on-site generation, was 3,675 billion kWh, the DoD share represents 0.8 percent of the nation's consumption.

DoD installations are totally dependent on private industries to provide all of their lighting, induction motors, and electronic equipment products. Although DoD is a large purchaser of these products, it cannot single-handedly shape the underlying market forces driving these industries. For example, DoD installations purchase air conditioning systems that are off-the-shelf products already developed and marketed by the industry. This procurement practice minimizes DoD's total costs by avoiding separate and unique development costs and by taking advantage of widely available trained personnel for operation and maintenance of the system.

Figure 2-9 shows a breakout of electricity generation methods in the U.S. DoD's purchasing power has little bearing on how the industry generates electricity.

Figure 2-9. Energy Sources of U.S. Electricity Generation



Renewable Energy Market

Renewable energy includes energy produced from solar, wind, biomass, hydropower, and geothermal sources. In FY03, DoD either purchased or self-generated 423 million KWH of electricity from renewable energy. DoD is required by Executive Order 13123 to promote the use of renewable energy, where cost effective.

Renewable technologies are projected to grow slowly because of the relatively low costs of fossil-fired generation, and because markets favor less capital-intensive technologies to build new capacity. About 60 percent of future projected growth is for grid-related electricity generation (including combined heat and power), and the remainder is for dispersed heating and cooling, industrial uses, and fuel blending.

Summary

The energy requirements for DoD are absolutely essential for day-to-day and contingency operations. Continuing changes in force structures and positioning of forces may alter the energy demand slightly, but DoD will undoubtedly remain dependent on the energy industry in meeting its future energy needs.

Chapter 3
Hydrogen Development

INTRODUCTION

The potential ability to generate fuel for military purposes anywhere, and at any time, should cause hydrogen to be an intriguing prospect for DoD. This chapter provides information to help objectively assess the prospects, applications, and timing associated with DoD's use of hydrogen. We discuss the following:

- Current hydrogen production and consumption in the United States
- Barriers to the use of hydrogen as a fuel
- The status of hydrogen-related technology development
- Commercial applications with the highest potential for initial introduction of hydrogen.

The hydrogen energy chain—production, distribution, storage, and conversion—has been successfully prototyped and demonstrated in applications representative of military power requirements. The nation's current industrial gas sector, which supplies hydrogen primarily for use in manufacturing processes, is not the basis for the military's implementation of hydrogen energy. However, it does provide over 50 years of confidence in engineering practices and in the processes for handling hydrogen safely.

Current military logistics systems are built around liquid petroleum and the use of purchasable commodities. Given the importance of fuel for DoD's mission, it is appropriate for contingency plans to anticipate oil and natural gas supply disruptions. It is also prudent to prepare for increasing volatility in conventional fuel prices. As we look ahead to meeting future military energy requirements, hydrogen is a potentially attractive option. It can be produced by multiple processes, and can be derived from a variety of renewable and fossil sources. For both military and non-military purposes, it can be used for portable, stationary, and vehicle power generation.

DoD has a history of successful leadership in adapting new energy systems. For example, geothermal combined heat and power is used by U.S. forces in Iceland. At present, the services within DoD support activities related to advancing progress on hydrogen energy technologies. However, these are not as coordinated as they could be, particularly given the potential. Some of the most important activities within DoD focus on using hydrogen at different ends of the scale,

specifically, power packs carried by individual soldiers in the field and distributed stationary systems providing power for base facilities. The military use of fleet vehicles that run on hydrogen fuel is also a topic that warrants attention by DoD planners.

OVERVIEW OF HYDROGEN AND FUEL CELLS

Hydrogen is a colorless, odorless, tasteless, and nonpoisonous gas. It is the lightest element in the periodic table of the elements, and the most abundant element in the universe. Because it combines so readily with other elements, it is not generally found in its pure form. Combined with oxygen, it makes up the water that covers 70 percent of the Earth's surface. Hydrogen is present in all organic matter, including plants and fossil fuels.

The energy in 1 kilogram of hydrogen is roughly equivalent to the energy in one gallon of gasoline. Like gasoline, hydrogen is highly flammable. It can be ignited with a small amount of energy. Having a wide flammability range, it can ignite and burn when it comprises between 4 percent and 74 percent, by volume, of a mixture with air. However, it diffuses quickly; its buoyancy and diffusivity make it hard to contain and difficult to ignite in open air. The combustion of hydrogen produces no emissions of carbon dioxide, particulate matter, or sulfur. The amount of energy produced by hydrogen, per unit weight of fuel, is about three times the energy in an equal weight of gasoline. On the other hand, the energy per unit volume of hydrogen, at a pressure of 5,000 psi, is less than one-tenth of the energy in an equal volume of gasoline.

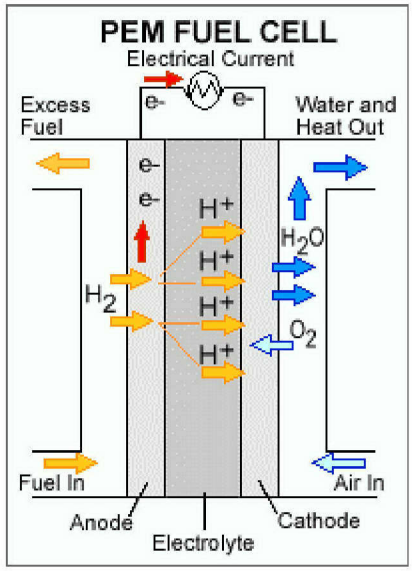
A number of processes can be used to separate hydrogen from the compounds in which it is found, primarily fossil fuels and water. Once separated, the resulting hydrogen can be burned in an internal combustion engine to produce power, or converted into electricity by a fuel cell. In a fuel cell, the fuel is oxidized, as in an internal combustion engine, but without burning. This "electrochemical" energy conversion process releases the fuel's energy in the form of electricity and heat.

A fuel cell power system has many components, but its heart is a "stack" of many thin, flat "cells" layered together, each of which generates an electrochemical reaction that produces power. A single cell generates a small amount of electricity (enough for a small light bulb), but many cells stacked together can provide enough electrical power to run an automobile.

Fuel cells and batteries convert chemical energy into electricity very efficiently. Unlike a fuel cell, however, the reactants in a battery are stored internally; when they are used, the battery must be either recharged or replaced. In the case of a fuel cell, the fuel is stored externally in a tank, and air is obtained from the atmosphere. As long as the tank contains fuel, the fuel cell will produce electricity and heat.

Scientists and engineers are working on developing different types of fuel cells. The most promising for many types of applications, particularly vehicles, is the relatively small proton exchange membrane (PEM) fuel cell. A single PEM fuel cell consists of an electrolyte membrane sandwiched between two catalyst layers (Figure 3-1). The electrolyte is a polymer plastic membrane with a thickness of 50 to 175 microns, equivalent to a few sheets of paper.

Figure 3-1. Components of a PEM Fuel Cell



Source: Department of Energy, Office of Energy Efficiency and Renewable Energy Web site, www.eere.energy.gov/hydrogenandfuelcells.

The catalysts help start the reactions that produce electricity. When hydrogen is fed to a PEM fuel cell and encounters the anode, the hydrogen molecules release electrons and protons. The protons migrate through the electrolyte membrane to the cathode, where they react with oxygen to form water. The electrons travel around the electrolyte, through an external wire, to complete the circuit, providing an electrical current in the process. The operating temperature of a PEM fuel cell is from 160°F to 185°F.

In addition to PEMs, several other types of fuel cell technologies are being developed.

- Alkaline fuel cell. This is one of the oldest designs, which has been used in the U.S. space program. It is relatively expensive, compared to other designs, and is not considered a likely candidate for commercialization.
- Phosphoric acid fuel cell (PAFC). This type has potential for use in small stationary power generation systems. It operates at a higher temperature than PEM fuel cells, so it has a longer warm-up time.

- Solid oxide fuel cell (SOFC). These fuel cells are best suited for large-scale stationary power generators that could provide electricity for factories or towns. They operate at very high temperatures, above 1,800ºF. An advantage is that steam produced by the fuel cell can be channeled into turbines to generate more electricity, improving the overall efficiency of the system.

- Molten carbonate fuel cell (MCFC). These are also best suited for large stationary power generators. They have a lower operating temperature than the SOFC; thus the design and materials can be less expensive.

HYDROGEN PRODUCTION AND DISTRIBUTION

According to the DOE,[1] the U.S. hydrogen industry currently produces 9 million tons of hydrogen per year. Nearly all of this production is for industrial use. If all of the domestic production were to be used as a fuel, 9 million tons could power 20 to 30 million cars, or 5 to 8 million homes, for 1 year.

Production Sources

U.S. hydrogen production accounts for 22 percent of the world's production, which is over 40 million tons annually. Steam methane reforming of natural gas, a process that converts hydrocarbon fuels into hydrogen and carbon monoxide, is the process employed for 95 percent of U.S. production. Worldwide, 48 percent of hydrogen is produced from natural gas, 30 percent from oil, 18 percent from coal, and the remaining 4 percent via electrolysis of water.

Most hydrogen produced in the U.S. is a product of one of four major industrial gas companies: Air Products and Chemicals, Praxair, Air Liquide America, and the BOC Group. Although hydrogen is available in many purity levels, fuel cells require a purity of 99.99 percent.

Distribution Methods

About 64 percent of U.S. production is "captive," that is, produced and used "inside the fence" of a major industrial complex, such as a petroleum refinery. The rest, called "merchant hydrogen," is transported by pipeline or trucks using cylinders, tube trailers, and cryogenic tankers. A small amount is shipped by rail or barge.

Hydrogen distribution via high-pressure cylinders and tube trailers has a range of 100-200 miles from the production facility. For longer distances (up to 1,000 miles), hydrogen is usually transported as a liquid in super-insulated, cryogenic, over-the-road tankers, railcars, or barges, and then vaporized for use at the

[1] Department of Energy, Office of Energy Efficiency and Renewable Energy Web site, www.eere.energy.gov/hydrogenandfuelcells.

customer site. Pipelines, which are owned by merchant hydrogen producers, are limited to a few areas in the U.S. where large hydrogen refineries and chemical plants are concentrated, such as Indiana, California, Texas, and Louisiana.[2]

Multiple Production Options

One important potential benefit associated with hydrogen is the diversity of production options. Taken together, these options enable hydrogen to be derived from every possible energy source—fossil fuels, renewable resources, and nuclear processes. Hydrogen can be reformed from natural gas, petroleum, petroleum products such as gasoline and JP8, methanol and ammonia. Renewable resources include biomass, sunlight, wind, waste materials, geothermal energy, and hydropower.

Processing technologies employed for hydrogen production can be classified as thermochemical, electrolytic, photolytic, and biological.

- *Thermochemical* production uses heat and chemical reactions to convert hydrocarbon feedstocks to hydrogen. This category includes steam methane reforming, partial oxidation of methane, and biomass gasification and pyrolysis. High- and ultra-high-temperature thermochemical hydrogen production that uses nuclear waste heat or solar heat may be viable with the development of appropriate water-splitting chemical process cycles and materials.

- *Electrolytic* production uses electricity to split water into hydrogen and oxygen. Most electricity today is generated using fossil fuels, but the potential exists for electrolysis that uses more electricity generated from renewable sources. Currently, electrolysis is used primarily for applications requiring small volumes of high purity hydrogen (or oxygen, such as that used in submarines).

- *Photolytic* production uses the energy from sunlight to split water into hydrogen and oxygen. Emerging direct water-splitting technologies include photobiological systems and photoelectrochemical systems.

- *Biological* systems use microbes to break down a variety of biomass feedstocks into hydrogen.

Appendix A of DOE's *Hydrogen Posture Plan*[3] provides a summary of the multitude of hydrogen production and delivery options. It also presents information on resource flows, fossil fuel consumption, and greenhouse gas emissions for several potential hydrogen production pathways. The most appropriate methods employed in a given circumstance will be a function of feedstock or resource availability, the quantity of hydrogen required, and the hydrogen purity needed.

[2] Ibid.

[3] U.S. Department of Energy, *Hydrogen Posture Plan*, February 2004.

Other choices will need to be made during evolution of a national hydrogen infrastructure.[4] Hydrogen production can be characterized as centralized or distributed. A distributed infrastructure consists of natural gas or other fuel reformers, and/or electrolyzers, located at the point of use. Points of use include locations such as refueling stations and stationary power generation sites. Distributed production should reduce hydrogen delivery costs. The alternative approach is to produce hydrogen centrally using any of a variety of feedstocks, fossil or renewable. To eliminate greenhouse gas emissions when using fossil fuels, carbon sequestration is needed for either distributed or centralized production. To be commercially viable, centralized production requires development of a distribution infrastructure.

Another production option is co-production of hydrogen, heat, and power, employing a regional, or "power park," concept. The hydrogen can be used in a fuel cell to produce electricity in addition to being sold for use as a fuel for powering vehicles.

"Hybrid" hydrogen production options also exist. For instance, a base feedstock can be centrally transformed to a chemical liquid hydrogen carrier, which can then be transported at low cost to distributed power generation and/or vehicle fueling facilities.

USES FOR HYDROGEN

At the present time, most hydrogen is used as a feedstock, an intermediate chemical, or a specialty chemical. Over 90 percent of the hydrogen produced in the U.S. is utilized by the petroleum refining and petrochemical production industries. Another 6 percent is required for a variety of production processes in the metals, electronics, edible fats and oils, and glass industries. The hydrogen portion of the industrial gas business is increasing at a rate of 8 percent annually.

The National Aeronautics and Space Administration (NASA) is the primary user of hydrogen as a fuel, accounting for about 1 percent of U.S. production. Other uses of hydrogen for fuel purposes are so small that statistics are not yet collected by organizations such as DOE's Energy Information Administration. Very small amounts are used for fuel cells that serve as backup power units, or for demonstration fuel cell vehicles. For such applications, hydrogen is either trucked in or produced by small on-site natural gas reformers or electrolyzers.

The DESC purchases liquid and gaseous hydrogen to be used by the Air Force, NASA, and contractors supporting DoD missions. Liquid hydrogen is used as a missile propellant and for cryogenic cooling for industrial operations, laser firing,

[4] U.S. Department of Energy Hydrogen, Fuel Cells and Infrastructure Technologies Program, *Multi-Year Research, Development and Demonstration Plan for 2003-2010* (Draft), June 2003.

and research. Gaseous hydrogen is purchased for support of short-term engine testing and laser firing experiments.[5]

DoD, as well as other military organizations around the world, is among the users of limited amounts of hydrogen. Howaldtswerke-Deutsche Werft AG (HDW) is manufacturing four fuel cell powered U-31 submarines for the German navy.[6] The company has orders for additional submarines from Greece, Italy, and South Korea. The PEM fuel cell modules for these boats are being made by Siemens Industrial Solutions. Israel has also stated its intention to purchase two fuel cell submarines.

HYDROGEN COSTS

Our discussion of costs focuses on pure hydrogen (99.99 percent), the purity required for fuel cells.

In general terms, hydrogen produced by large-scale reformation of natural gas (CH_4, or methane) costs approximately $1 per kilogram (kg). This cost is only for production and does not include transportation and delivery. Hydrogen produced by electrolysis (splitting water) costs approximately $2 per kg, when small to medium scale processes are used. The domestic industrial gas firms sell hydrogen in a price range of $6-$71 per kg. The price is dependent on the customer, application, delivery location, order size/frequency, and market defense strategy of the seller. NASA has successfully created a liquid hydrogen market with competitive pricing, but in the U.S. it is unique in its leverage.

Appendix III of *An Integrated Hydrogen Vision for California,*[7] a white paper by University of California authors, includes tabulations of cost estimates for hydrogen production and delivery. Figure 3-2 shows the range of estimates for delivering hydrogen via a variety of pathways.

The 2004 National Academies (National Academy of Science (NAS)\National Research Council (NRC)) report on hydrogen provides the results of an extensive analysis of current and future hydrogen costs.[8] These results are detailed in Chapter 5 and Appendix E of the NAS/NRC document. The University of California's white paper has consolidated the results.

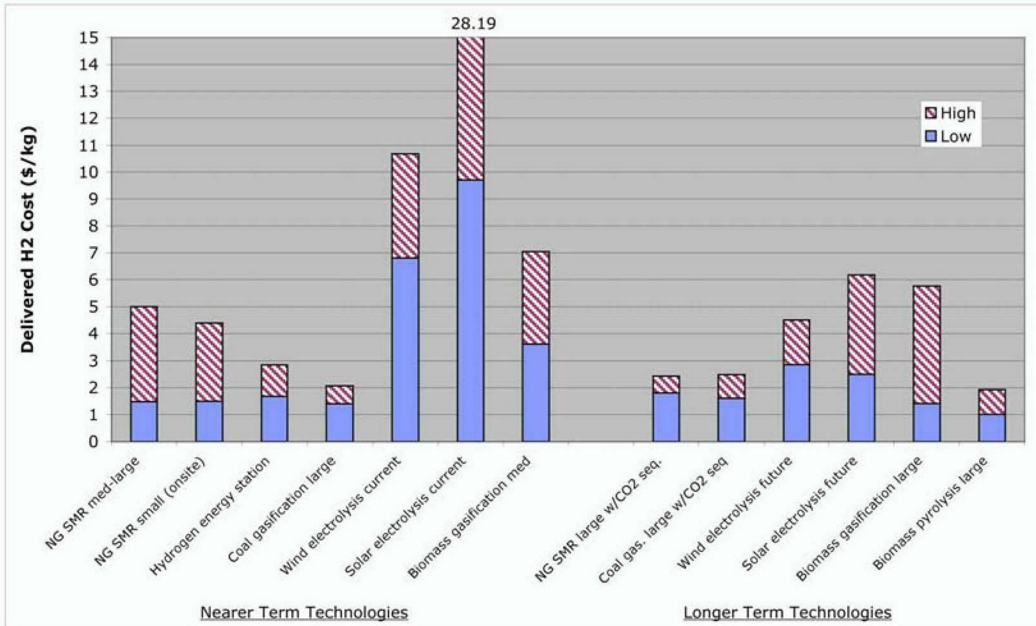
[5] Briefing on DESC Hydrogen Management, San Antonio TX, July 2004.

[6] International Clearinghouse for Hydrogen Based Commerce newsletter, www.ch2bc.org.

[7] T. Lipman, D. Kammen, et al., *An Integrated Hydrogen Vision for California*, University of California, July 2004.

[8] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, The National Academies Press, 2004.

Figure 3-2. Ranges in Delivered Hydrogen Cost Estimates

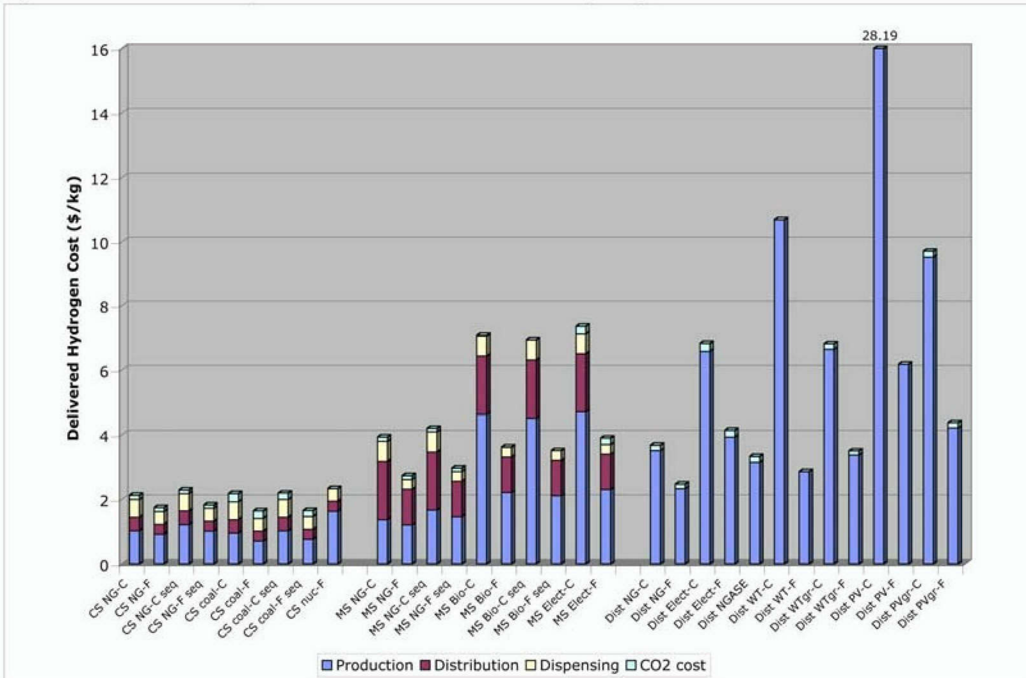


Notes: Various sources - see Appendix III for details. The ranges shown are taken from many different sources, including those with assumptions that may be somewhat inconsistent with regard to production scale, interest rates, and other key assumptions. Wider and narrower ranges between high and low costs thus tend to reflect the relative numbers of studies for each pathway, rather than inherent uncertainties in costs for each pathway. Also note that a kilogram of hydrogen contains about as much energy as a gallon of gasoline, but hydrogen-powered vehicles are expected to have ~1.5-3x higher fuel economy than comparable conventional vehicles depending on the technologies used and other vehicle design variables.

Source: *An Integrated Hydrogen Vision for California,* White Paper/Guidance Document, Prepared with Support from the Steven and Michele Kirsch Foundation, July 9, 2004.

Figure 3-3 shows a comparison of costs to deliver hydrogen as a fuel. The estimates provide a range of costs that include consideration of feedstocks (natural gas, biomass, etc.), state of technology (current and future), production (centralized and distributed) and carbon sequestration costs.

Figure 3-3. An "Internally Consistent" Set of Delivered Hydrogen Cost Estimates



Source: NAS/NRC, 2004. Notes: Bio = biomass gasification; C = current technology; CS = large central station; Dist = distributed production at small scale; Elect = grid-power electrolysis; F = future technology; gr = grid assisted electrolysis; MS = medium-scale; NG = natural gas SMR; PV = solar photovoltaic powered electrolysis; seq = with carbon sequestration; WT = wind turbine powered electrolysis. CO_2 cost = carbon disposal cost and/or carbon tax of $50 per ton.

Source: *An Integrated Hydrogen Vision for California,* White Paper/Guidance Document, Prepared with Support from the Steven and Michele Kirsch Foundation, July 9, 2004.

BARRIERS TO INCREASED USE OF HYDROGEN AS AN ENERGY CARRIER

Before the country achieves significant use of hydrogen as a fuel for either civilian or military purposes, it must successfully address a number of challenges encompassing production, delivery, storage, and conversion. Some technologies are yet to be fully developed. Some already developed technologies must be thoroughly tested, proven reliable, and further refined. Costs of technologies need to be reduced, often by an order of magnitude or more. Other needs include development of codes and standards to ensure safety, as well as education for both those handling hydrogen and the general public. Current hydrogen producers are not well positioned to make the technology advances required for hydrogen use in electrical power generation and vehicle applications.

The barriers are well documented by government agencies (particularly the DOE), hydrogen associations, and industry. Drawing on these documents, this section

summarizes the major obstacles. Table 3-1 provides a summary of the key technical challenges identified by DOE.[9]

Table 3-1. Barriers to the Use of Hydrogen

Element	Key technical challenges
Production	◆ Low-cost hydrogen production techniques ◆ Low-cost and environmentally sound carbon sequestration technologies ◆ Advanced hydrogen production techniques from fossil fuel, renewable, and nuclear sources.
Delivery	◆ Less expensive hydrogen transport technology ◆ Appropriate codes and standards ◆ Right of way for new delivery systems.
Storage	◆ Low-cost, lightweight, and energy-dense storage systems.
Conversion	◆ Low-cost, durable, and reliable fuel cells that can be mass produced.
Applications	◆ Successful field tests and demonstrations ◆ Supportive public policies to stimulate infrastructure and market readiness.
Codes and standards	◆ Published fuel gas code that includes hydrogen ◆ Published safety standard for certification of a fuel cell vehicle ◆ Insurance rating of hydrogen energy systems ◆ Training and certification program.

Production

DOE's *Multi-Year Research, Development and Demonstration Program Plan for 2003-2010*[10] identifies 30 barriers associated with hydrogen production. It discusses obstacles related to five production approaches.

Distributed Production from Natural Gas or Liquid Fuels

Barriers include fuel processor capital costs; the need for improved system optimization; availability of feedstock and clean water; cost-effective sequestration of carbon dioxide emissions; and system control issues.

[9] U.S. Department of Energy, *Hydrogen Posture Plan,* February 2004.

[10] U.S. Department of Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program, *Multi-Year Research, Development and Demonstration Plan for 2003-2010* (Draft), June 2003.

Production from Biomass

Feedstock and capital costs are too high for hydrogen produced from biomass to be competitive. Higher process efficiencies are required for gasification, pyrolysis, and reforming technologies. Fermentation microorganisms for hydrogen production have not been sufficiently evaluated.

Photobiological and Photoelectrochemical Generation

Research is needed to identify ways to increase light conversion efficiency. Improved forms of algae must be identified. The rate of hydrogen production from photosynthetic microorganisms is far too low. Inhibition of the hydrogen-producing enzymes needs to be reduced or eliminated. Sufficiently durable materials have not been identified. Techniques for manufacturing appropriate photoelectrochemical materials are needed.

Water Electrolysis

The cost of electrolysis equipment, combined with the cost of grid electricity in many locations, impedes adoption of competitive electrolysis technology. Low-cost, high-pressure materials must be developed to support high-pressure compression technologies. Low-cost, carbon-free electricity sources are needed. In this connection, development of small- and large-scale integrated renewable electrolysis systems is needed. Electrolysis systems that can produce both hydrogen and electricity need to be evaluated.

High- and Ultra-High-Temperature Thermochemical Production

Thermochemical technology components and subsystems (nuclear and solar) have not been evaluated. Cost-effective, durable materials are needed to withstand the very high temperatures involved, and the thermal cycling associated with solar concentrator systems. Permitting and licensing procedures severely limit the ability to build nuclear facilities. Improved solar collection and concentration technologies are needed.

Delivery and Distribution

As a product of centralized, large-volume production facilities, hydrogen must be transported to the point of use. If produced near its point of use, hydrogen must still be moved within a refueling site or stationary power facility, and the economy of large-scale production is lost. Due to its low volumetric energy density and other factors, the transportation and delivery of hydrogen, with their associated infrastructure issues, are marked by significant costs and inefficiencies.

There are several barriers associated with delivery of hydrogen. There is insufficient understanding and analysis of the trade-offs, advantages, and disadvantages

of hydrogen delivery alternatives. Many site-specific, local, and regional issues can influence the approach to integrating hydrogen production and use.

Hydrogen compression has been advancing under pressure by the automotive manufacturers to increase vehicle range, and therefore a vehicle's onboard storage capacity. Compression is still considered inefficient (and expensive) in the systems engineering of a fueling station. The state of the art is 5,000 psi storage, which can be implemented without scientific advances, but 10,000 psi storage is foreseen in the near future. A 15,000 psi equivalent is obtainable by using liquid hydrogen aboard the vehicle, but this requires the system to have cryogenic (supercold) equipment. Liquefaction of hydrogen has become highly efficient (and relatively less expensive) in terms of energy, but still remains a challenge because of the associated capital equipment expenditure.

The capital cost of new hydrogen pipelines is high. Costs of storage at refueling stations and other points, surge capacity requirements, and transport containers are also too high. In addition, a solution is needed for preventing or mitigating hydrogen embrittlement of pipeline materials. Current solid and liquid hydrogen transport technologies have high costs, insufficient energy density, and poor hydrogen release and regeneration characteristics.

Storage

Improved technology for storage is widely considered to be the most critical enabling technology required for the successful commercialization of hydrogen as a fuel. Finding better storage options, both for on-board vehicle applications and for off-board applications, is often cited as the most daunting of the many technological challenges associated with hydrogen. The DOE's *Multi-Year Plan* states the following:

> For transportation applications, the overarching technical challenge for hydrogen storage is how to store the necessary amount of hydrogen fuel required for conventional driving range (greater than 300 miles), within the constraints of weight, volume, durability, efficiency, and total cost. … [V]olume is an important consideration in many off-board installations where space is limited, especially at refueling stations.[11]

Cost is also cited as an important factor for both off-board and on-board storage. DOE notes that costs must be reduced by a factor of almost 10 for storage systems, in addition to the substantial improvements required in system weight and volume. In its plan, DOE identifies 25 barriers associated with hydrogen storage. Besides cost, weight, and volume, these include:

- Efficiency in use of energy for hydrogen compression, hydrogen liquefaction, and moving of hydrogen in and out of reversible solid-state materials
- Durability of hydrogen storage systems

[11] Ibid.

- Refueling time requirements
- Insufficiency of analyses for life cycle costs and efficiencies
- Need for new materials of construction and fabrication techniques
- Insufficient information on storage tank performance and failure modes
- Hydrogen boil-off requirements with current cryogenic storage
- The need for test protocols, dispensing technology, and improved cycle life for reversible solid-state hydrogen storage systems
- Improved regeneration processes and by-product removal for chemical hydride storage systems.

Energy Conversion

During the past decade, fuel cell technology has been a topic of increasing attention by manufacturers, power producers, and those with environmental interests. This attention has been manifested by substantial financial investments. The reason for increasing interest is the potential for fuel cells to provide power more cleanly, and with higher energy conversion efficiency, than current technologies, notably the internal combustion engine.

Depending on the type of fuel cell, hydrogen or any hydrogen-rich fuel can be utilized as a source of electrons for the production of electricity. For transportation propulsion applications, most research and investment is aimed at direct hydrogen fuel cells, that is, machines requiring a supply of high purity hydrogen. Research and development being pursued by both industry and government includes on-board fuel reforming, in which fuels supplied by existing infrastructure—including natural gas, gasoline, and other hydrocarbon fuels—are processed to produce hydrogen. In August 2004, however, DOE's Office of Hydrogen, Fuel Cells and Infrastructure Technologies announced its intention to close out its support for development of vehicle on-board reforming technologies.[12]

Similar to the situation addressed previously, there are barriers to the successful development and introduction of fuel cells on a commercial scale. Given the dependency of fuel cells on hydrogen, their potential for widespread use is closely related to resolving the issues associated with hydrogen production, delivery, and storage. The following barriers, however, have been identified specifically for the

[12] DOE News, *DOE Discontinues On-Board Fuel Processor R&D*, www.eere.energy.gov/hydrogenandfuelcells, August 6, 2004.

fuel cell, or energy conversion, element of the hydrogen energy chain.[13] Cost and efficiency are two of the most significant barriers for this element as well.

Transportation Systems

Barriers to fuel cell energy conversion for transportation systems include the following:

- Automotive compressors/expanders that minimize parasitic power consumption and meet packaging and cost requirements are not available.
- Improved sensors are needed to meet performance and cost targets.
- Current heat exchangers do not accommodate the low temperature differential available.
- Development of a validated system model and periodic benchmarking of fuel cell systems and components are required.

Distributed Generation Systems

The following are among the energy conversion barriers for distributed generation systems:

- Durability must be improved to compete against other distributed power generation systems.
- Heat utilization is poor. More efficient heat recovery systems and improved system designs are necessary.
- Energy management strategies and power electronics improvements are needed.
- The startup time for fuel cell systems is too long.

Fuel Cell Components

Several obstacles must be overcome with respect to fuel cell components, including the following:

- Stack material and manufacturing costs are too high to be competitive, particularly for vehicle applications.
- Durability of fuel cell stacks must be improved, including tolerance to impurities.

[13] U.S. Department of Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program, *Multi-Year Research, Development and Demonstration Plan for 2003-2010 (Draft)*, June 2003.

- Electrode performance depends on precious metal loading, which is too high to meet cost targets.
- Higher temperature membranes, and/or improved heat utilization, cooling, and humidification, are needed for more effective thermal and water management.
- On-board fuel processing presents a number of additional barriers, as does off-board decentralized processing of fuels to extract hydrogen.

Codes and Standards

To enable the acceptance of hydrogen in consumer products, new building codes, vehicle codes, and other technical standards need to be developed and adopted by federal, state, and local governments. Codes and standards are generally recognized as a significant institutional barrier to deploying hydrogen technologies and developing a hydrogen-based economy. This issue is not only a national challenge, but also a global one. The International Standards Organization (ISO) implemented a multi-year process simply to reach agreement on the definition of hydrogen fuel. This international collaboration is important to assure that hydrogen fuel purchased worldwide is chemically consistent with the equipment designed and deployed by all ISO nations. A hydrogen fuel specification is currently under development. Major areas for which standards are being developed by various organizations, domestically and internationally, are stationary fuel cells, fuel cell vehicles, hydrogen refueling stations, and hydrogen transportation.

Barriers to rapid progress on codes and standards include:

- Competition among consensus standard-setting organizations
- Limited state funds for adoption of codes and standards
- The large number of local government jurisdictions
- Variability in quality and availability of training for code officials
- The large number of individuals and organizations involved in the consensus standard-setting processes worldwide
- Complications associated with international competitiveness and licensing issues
- Cost for industry to be fully and effectively engaged in international technical committees
- Competitiveness in copyrighting of published standards

- Acceptance of different families of codes by different jurisdictions
- Insufficient technical data.

Summary of Barriers

Numerous challenges must be successfully addressed in order for hydrogen to become a fuel of choice. In general, we expect that overcoming the technical and cost barriers for powering vehicles will require at least a decade. A business case for using hydrogen fuel cells in high-value stationary applications could be made within a decade. However, even in those cases, significant questions cast doubt on the ability to supply hydrogen cost-effectively and reliably.

With regard to relatively near-term potential military uses of hydrogen, the reliability of systems is not yet supported by adequate test durations. Components and devices in the hydrogen energy chain have not achieved the mean time between failures (MTBF) that military uses demand. While industry has made significant progress in reducing the bill of materials for fuel cells over the past few years, much remains to be accomplished. Packaging is often more demanding for military requirements and equipment.

TECHNOLOGY INITIATIVES AND ACTIVITIES

Many organizations, in the U.S. and around the world, are making significant investments to help hydrogen become a safe, competitive, and preferred fuel. In a Worldwatch Institute paper published in 2001,[14] Seth Dunn noted that more than 100 organizations were engaged in research and development of PEM fuel cells.

The Worldwatch paper provided examples of companies working in partnerships to pursue stationary power applications for fuel cells. Companies mentioned include small startups such as H Power, Ballard, Alstom, and Plug Power. During the decade of the 1990s, the world's major automakers invested billions of dollars in fuel cell development. By 2000, pilot tests of fuel cell buses running on liquid or compressed hydrogen were under way, with more on the drawing board. During the years since 2000, early fuel cell powered automobiles and light trucks have been made available for testing in real-world conditions.

Also during the 1990s, government organizations devoted more attention to creating and managing more productive technology development partnerships with industry. The partners together analyzed and agreed on technology goals, and worked on plans to achieve them. Within the federal government's Partnership for a New Generation of Vehicles (PNGV), and then the DOE's FreedomCAR Partnership, General Motors, Ford, and DaimlerChrysler voiced the need for more significant investment by government in development of the hydrogen infrastruc-

[14] Worldwatch Institute, *Hydrogen Futures: Toward a Sustainable Energy System,* Worldwatch Paper #157, Seth Dunn, August 2001.

ture to support fuel cell vehicles. This factor contributed to President Bush's proposal for more aggressive development of hydrogen related technology.

Research, Development, and Demonstration

Organizations investing significant funds in the development of hydrogen related technology include both private industry and government agencies.

INDUSTRY

In a 2003 report,[15] Robert Rose of the Breakthrough Technologies Institute stated, "Perhaps the most encouraging evidence to date of the commercial potential of fuel cells is the enormous investment the private sector has committed to the technology since 1995. Estimates of annual spending range from $1 billion to $3 billion." In addition to substantial work funded by the automotive companies, significant research, development, and demonstration (RD&D)—more than $2 billion over the last 5 years—has been claimed by the oil and gas industry, fuel cell companies, and hydrogen equipment companies. Shell and ChevronTexaco cite investments in small specialty companies. The industrial gas companies engage in RD&D for strategic marketing purposes. Publicly listed companies focused on hydrogen energy have a combined market capitalization exceeding $2 billion. These companies have the financial ability and motivation to move beyond RD&D to commercialization if hydrogen energy becomes profitable.

Vehicle Manufacturers

The world's major automotive corporations both fund and perform research and development. General Motors (GM), for example, has established extensive hydrogen fuel cell research and development (R&D) facilities in the U.S. and Europe. The Hy-Wire, a GM concept vehicle with a fuel cell propulsion system housed entirely in an 11-inch thick skateboard-like chassis, has been well publicized, as have the company's projections for commercialization of fuel cell vehicles. Its web site states, "GM has made great strides in solving many of the challenges inherent in fuel cell technology, including problems with freezing."[16] GM claims that its efforts have resulted in increasing the power density of its fuel cell stack technology tenfold in just 2 years. In June 2004, one of GM's fuel cell prototype vehicles set a world record distance of over 6,000 miles through 14 countries. The vehicle was accompanied, however, by the trucks required to transport the hydrogen for refueling.

Since hydrogen is not readily available for vehicles, companies like GM are also engaged in partnerships that can provide stationary power applications for their fuel cell advances. A GM prototype stationary fuel cell unit is generating power for its New York fuel cell development facility. Dow Chemical and GM are work-

[15] Robert Rose, *Fuel Cells and Hydrogen: The Path Forward,* Breakthrough Technologies Institute, February 2003.

[16] www.gm.com/company/gmability/adv_tech/400_fcv, August 2, 2004.

ing on a joint venture to demonstrate the viability of hydrogen fuel cells for large industrial power systems. The hydrogen available as a by-product of chemical manufacturing is being used in a GM fuel cell unit to generate 75 kW of power at Dow's facility in Freeport, TX.

Recognizing that hydrogen fuel cell vehicles will require the availability of competitive hydrogen fuel, GM is also creating partnerships with major companies, including Shell, ExxonMobil, BPAmoco, and ChevronTexaco. Earlier this year, ground was broken in Washington, DC, for a hydrogen refueling station being constructed as part of joint venture between GM and Shell Hydrogen. GM has other strategic partnerships with Toyota, Suzuki, BMW, Quantum, General Hydrogen, Hydrogenics, Giner Electrochemical Systems, and the California Fuel Cell Partnership.

In July 2004, Ford Motor Company and DaimlerChrysler revised their memorandum of understanding with Ballard, a Canadian-based fuel cell development company. Having worked together for some time on fuel cell development, the three companies further defined the roles and responsibilities within their alliance, and established program funding requirements. As part of the updated agreement, DaimlerChrysler and Ford are acquiring Ballard's vehicular fuel cell systems business, and will conduct research, development, and manufacturing of vehicular fuel cell systems. The two automakers will provide up to $58 million for Ballard's R&D on the next two generations of vehicle fuel cells and its next-generation electric drive system. Ford is currently operating more than 25 third-generation Focus fuel cell vehicles in engineering and marketing fleets around the world.

The worldwide competition in the realm of vehicle fuel cell development is quite spirited. In December 2002, American Honda Motor Company delivered two Honda FCX vehicles to the city of Los Angeles. In June 2004, the first of two Honda fuel cell vehicles was delivered to California's South Coast Air Quality Management District (SCAQMD). The Honda fuel cell car was the world's first to be commercially certified as meeting all federal safety requirements, and by the California Air Resources Board (CARB) as a zero-emissions vehicle. Honda has 12 fuel cell cars on the road in the U.S. The company states it has developed a fuel cell that can start in sub-zero temperatures. The 2005 model FCX has a 5,000 psi compressed hydrogen gas storage tank, and a U.S. Environmental Protection Agency (USEPA)-rated driving range of 190 miles between refueling. This most recent model is also the first to be powered by a Honda-designed and manufactured fuel cell stack.

Earlier this year, Toyota delivered a third fuel cell vehicle to the University of California. Its platform is the Highlander midsize sport utility vehicle, which has a 90 kW fuel cell stack and 5,000 psi compressed hydrogen storage tanks. This delivery marked Toyota's 18th fuel cell vehicle on the roads in the U.S. and Japan. Its maximum range is about 180 miles. Toyota is working with CARB, the SCAQMD, Air Products, and Stuart Energy to establish hydrogen fueling stations in California.

Energy Companies

The world's major international petroleum companies have become increasingly active on hydrogen issues during the past few years. Shell Oil established a subsidiary, Shell Hydrogen, in 1999 to pursue and develop business opportunities related to hydrogen and fuel cells. Shell Hydrogen's public documents state that its aims are to produce hydrogen in whatever forms markets demand, and support the development of fuel processing devices and technical solutions to successfully convert fossil fuels to hydrogen. The company works with partners on hydrogen storage systems, hydrogen purification technologies, and fuel processing technologies. It is actively involved in demonstration projects around the world, having opened hydrogen stations in Tokyo, Reykjavik, Amsterdam, and Luxembourg in 2003. As mentioned previously, it is partnering with GM on a station in Washington, DC. Shell Hydrogen's mission includes providing venture capital to companies in the hydrogen sector. Its partners include the California Fuel Cell Partnership, GM, HERA Hydrogen Storage Systems, Icelandic New Energy, QuestAir, and Vandenborre Hydrogen Systems.

Another major international energy company, BPAmoco, also partners with vehicle manufacturers and government agencies on hydrogen projects, demonstrations, and testing programs. Its projects, including a number of hydrogen refueling stations, are located in the U.S., Europe, Australia, and Singapore. In April 2004, BPAmoco announced a major initiative with Ford that includes a network of hydrogen fueling stations in Sacramento, Orlando, and Detroit. This initiative was developed in response to the DOE hydrogen fleet infrastructure and demonstration project solicitation, and was among the projects selected by DOE for funding support. BPAmoco states that this and similar projects are part of the company's focus on identifying the most efficient pathways to the hydrogen economy.

Fuel Cell Developers

While some of the world's largest manufacturers are making substantial investments in hydrogen related technologies, the commitment of many small companies, including new startups, is also noteworthy.

PriceWaterhouseCoopers has published, in its 2003 Fuel Cell Industry Survey, financial information obtained from the annual reports of 16 North American publicly traded fuel cell companies. A company was included if its primary goal is fuel cell production and/or system integration and/or related fueling infrastructure; and it was a stand-alone public company based in Canada or the U.S. as of the end of 2002. Among the survey's findings were the following:

- R&D expenses accounted for a major portion of operational costs. Overall, R&D spending increased by $42 million between 2001 and 2002, to a level of $263 million.

- None of the companies were profitable in 2002, largely due to the high cost of low-volume production and the focus on R&D. Losses in 2002 totaled $405 million.
- Most public fuel cell companies are developing PEM fuel cells and related fueling infrastructure.
- The market capitalization of these companies fell by 70 percent in 2002.
- Public companies, as well as their privately-held counterparts, benefited from government programs promoting the development of fuel cell technology.

GOVERNMENT

During the past decade, government agencies—particularly in the U.S., Europe, and Japan—have steadily increased public funding to support hydrogen-related RD&D. Governments provide funding support to a variety of organizations that perform RD&D. Agencies are responsible for management and oversight of programs, but generally do not accomplish the actual work themselves.

Hydrogen Fuel Initiative

In his January 2003 State of the Union Address, President Bush announced his Hydrogen Fuel Initiative. One of its stated goals is to reverse America's growing dependence on petroleum by developing the technologies needed for a commercially viable hydrogen-fueled economy.

Through partnerships with the private sector and other government organizations, this initiative seeks to develop hydrogen, fuel cell, and infrastructure technologies needed to make it practical and cost-effective for consumers to choose to use hydrogen fuel cell vehicles by 2020. In addition to its energy security objectives, the initiative is a key component of the President's clean air and climate change strategies.

U.S. Department of Energy

In January 2002, the Secretary of Energy announced FreedomCAR, a partnership with the U.S. Council for Automotive Research, which represents General Motors, Ford, and DaimlerChrysler. A primary purpose of FreedomCAR is to plan, guide, and review research to advance the technologies needed to produce practical, affordable hydrogen fuel cell vehicles. The partners clearly recognized that an intensive vehicle fuel cell development effort must be complemented by a concurrent aggressive effort to develop the technologies and infrastructure needed to provide the necessary hydrogen fuel.

This recognition was a precursor to the Hydrogen Fuel Initiative. It also resulted in a DOE partnership with major energy providers. Thus, the FreedomCAR Partnership has evolved into the FreedomCAR and Hydrogen Fuel Partnership, which includes BPAmoco, ChevronTexaco, ConocoPhillips, ExxonMobil, and Shell Hydrogen. The overall plan produced by the partnership is expected to result in technologies for hybrid vehicle components, fuel cells, and hydrogen technologies.

For FY04, $159 million was appropriated to accomplish hydrogen and fuel cell research and development funded through the Hydrogen Fuel Initiative. To support hydrogen-related R&D, the President has requested $227 million in DOE's FY05 budget. With reference to the previous discussion regarding barriers, these funds are allocated for work to help achieve the following goals:

- Lowering the cost of hydrogen—Currently, delivered hydrogen is three to four times more expensive than gasoline (when hydrogen is produced from its most affordable source, natural gas). The Hydrogen Fuel Initiative seeks to lower that price enough to make hydrogen competitive with gasoline by 2010, and to advance the methods of producing hydrogen from renewable resources, nuclear energy, and coal with carbon capture and sequestration.

- Creating effective hydrogen storage—Current hydrogen storage systems are inadequate for the wide range of vehicles that consumers demand. The Hydrogen Fuel Initiative supports the exploratory research and development needed to meet the "grand challenge": to store the amount of hydrogen required for a conventional driving range (greater than 300 miles), within the vehicular constraints of weight, volume, efficiency, safety, and cost.

- Creating affordable hydrogen fuel cells—Currently, fuel cell systems are up to 10 times more expensive than internal combustion engines. The Hydrogen Fuel Initiative seeks to reduce the cost to affordable levels.

Within the DOE, the Hydrogen Fuel Initiative is funded and managed primarily by the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Program in the Office of Energy Efficiency and Renewable Energy (EERE). Table 3-2 shows funding for the major elements of HFCIT's program.

In April 2004, the Secretary of Energy announced a number of project awards, including those to five teams working on technology validation and demonstration.[17] Each of these teams is headed by a major international automaker and/or international energy company. These five projects are to be funded from the combination of the Infrastructure Validation element (Energy and Water Development

[17] U.S. Department of Energy Press Release, *Energy Secretary Spencer Abraham Announces $350 Million in Hydrogen Research Projects*, April 27, 2004.

appropriation) and the Technology Validation element (Interior and Related Agencies appropriation).

Table 3-2. DOE Funding for Hydrogen R&D

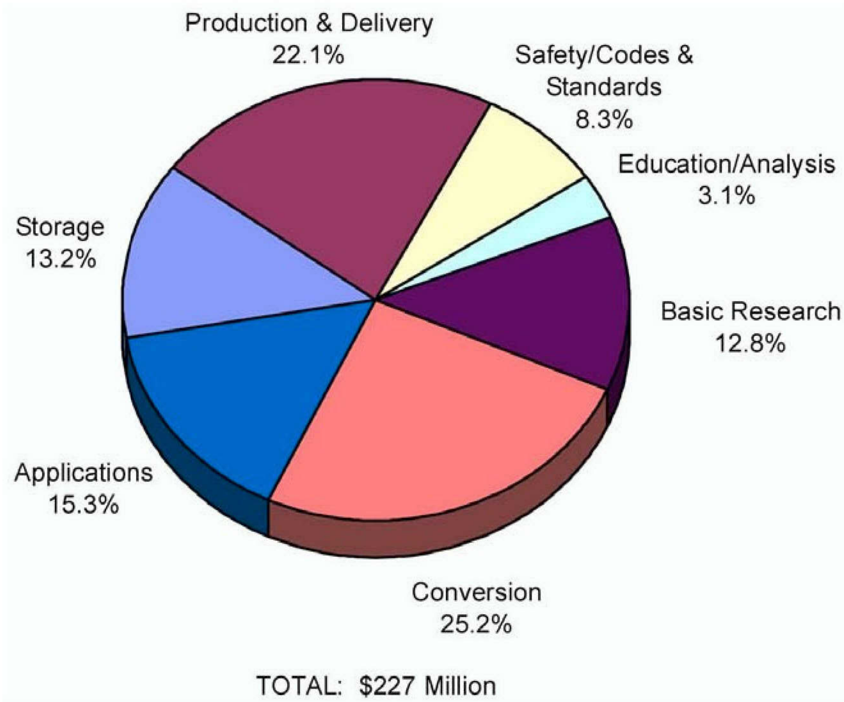
Program element	FY03 appropriation ($000)	FY04 appropriation ($000)	FY05 request ($000)
Hydrogen Production and Delivery	11,215	22,564	25,325
Hydrogen Storage	10,790	29,432	30,000
Infrastructure Validation	9,680	18,379	15,000
Safety, Codes and Standards, and Utilization	4,531	5,904	18,000
Education and Cross-Cutting Analysis	1,897	5,712	7,000
Transportation Systems	6,160	7,506	7,600
Distributed Energy Systems	7,268	7,408	7,500
Fuel Processing	23,489	14,815	13,858
Stack Components	14,803	25,186	30,000
Technology Validation	1,788	9,877	18,000

The ability of DOE to accomplish these projects expeditiously depends on congressional action in response to the FY05 request. Timely achievement of DOE's program goals, some of which are identified later in this report, are dependent on funding to implement its plans.

The primary hydrogen funding organization within DOE is EERE. However, other organizational elements in the department, and in other federal agencies, are also making important contributions. The total FY05 budget request of $227 million for hydrogen technology is devoted to several technology areas as shown in Figure 3-4.

As noted in DOE's *Hydrogen Posture Plan*, DOE-funded activities are being carried out consistent with plans developed primarily through cost-shared, public-private partnerships, including the FreedomCAR and Hydrogen Fuel Partnership.

Figure 3-4. DOE Budget Request for Hydrogen Technology, FY05



Source: United States Department of Energy, *Hydrogen Posture Plan: An Integrated Research, Development, and Demonstration Plan*, February 2004.

Industry R&D efforts are augmented by fundamental and applied research at national laboratories and universities. In addition to funding R&D through EERE, DOE also supports the following activities managed by other DOE organizational elements.

- *Hydrogen from coal*—The Office of Fossil Energy supports activities to develop low-cost, novel, and advanced technologies to produce hydrogen from coal. The work funded includes research on membranes, removal of carbon dioxide and trace components, and synthesis of gas-derived liquid fuels for fuel cell applications. Integration of developed technologies will enable production of affordable hydrogen from domestic fossil energy sources without environmental emissions.

- *Coal-fired electricity and hydrogen production*—In February 2003, President Bush announced a $1 billion, 10-year initiative to create a coal-based, zero-emissions power plant to produce electricity and hydrogen. Subsequently, DOE laid out plans for a FutureGen project to establish the technical and economic feasibility of producing electricity and hydrogen from coal while capturing and sequestering the carbon dioxide generated in the process.

- *Hydrogen production in conjunction with nuclear reactors*—DOE's Office of Nuclear Energy, Science and Technology plans to work with partners to demonstrate the commercial-scale production of hydrogen using heat from a nuclear energy system. Some advanced nuclear reactor designs operate at very high temperatures, making them candidates to drive highly efficient hydrogen production processes.

- *Solid State Energy Conversion Alliance (SECA)*—This joint government-industry effort seeks to achieve cost and technology breakthroughs in solid oxide fuel cell development. The overall goal is to create a solid oxide fuel cell with an output of 3 to 10 kW that can be mass-produced in modular form. These fuel cells could be used for power in many different applications. Technological challenges include fuel processing; controls and diagnostics; power electronics; modeling and simulations; and materials. A 5- to 10-fold cost reduction is required to reach the goal.

- *Basic research*—DOE's Office of Science supports basic R&D with the potential to achieve revolutionary advances in hydrogen production, delivery, storage, and conversion technologies in five critical areas: novel materials for hydrogen storage; membranes for separation, purification, and ion transport; design of catalysts at the nanoscale; bio-inspired materials and processes; and solar hydrogen.

U.S. Department of Defense

In his 2003 report,[18] Robert Rose notes that the Department of Defense "has identified fuel cells as a 'critical technology' whose development is vital to the nation's long-term defense." Consistent with this observation, DoD supports substantial R&D on fuel cell technologies. For example, the U.S. Army's Construction Engineering Research Laboratory (CERL), an element of the Corps of Engineers Engineer Research and Development Center (ERDC), has managed a number of activities during the past decade.

- *Installation and demonstration of phosphoric acid fuel cells (PAFC) at 30 DoD bases between 1994 and 1997*—This effort began in FY 1993 with an appropriation of $18 million. Seven of the fuel cells were configured to provide backup electrical power should the utility grid experience a power outage. Thermal output from the fuel cells has been used for various purposes. Three of these PAFC systems remain operational.

- *The Advanced Power and Energy Program*—The goals of this program include a "University Fuel Cells" initiative that supports critical research and development needs and contributes to advancement of fuel cell technologies for DoD applications. Other goals are to coordinate fuel cell testing activities, advance the fuel flexibility of solid oxide fuel cell systems,

[18] Robert Rose, *Fuel Cells and Hydrogen: The Path Forward*, Breakthrough Technologies Institute, February 2003.

and advance the transfer of DOE-supported technologies to DoD deployment.

- *Camp Roberts Fuel Cell Demonstration*—This installation is intended to demonstrate the capability of a fuel cell product to boost the readiness of a satellite communications facility by providing secure, reliable energy services.
- *Development of a solid oxide fuel cell (SOFC) power system using military diesel and JP8 fuels*—The core objective is to develop a viable diesel or JP8 fuel processing system for military-use SOFCs. The focus is on systems with up to 10 kW capacity. The emphasis is on full integration of the fuel processing system with the operational requirements of the SOFC stack. The contractors for this work are the Gas Technology Institute, the Air Force Research Laboratory (AFRL) at Tyndall Air Force Base, NexTech Materials, and the DoD Fuel Cell Test and Evaluation Center (FCTEC). The development team collaborates with DOE's SECA program and other SOFC development initiatives.
- *Logistics Fuel Reformer/Processor for Fuel Cell Mobile Electric Power Generation*—CERL partners with the AFRL on this project. The major objectives are to develop a micro-channel-based 100 kW processor to reform DoD logistic fuel to high purity hydrogen, and to design, build, and test a 100 kW processor/fuel cell demonstration.

ERDC/CERL is also a major sponsor of the FCTEC, which is operated by Concurrent Technologies Corp. in Johnstown, PA. FCTEC provides independent testing of fuel cell power plants for military and commercial applications. Its goal is to accelerate the development and commercialization of fuel cells.

Other DoD organizations funding fuel cell and hydrogen-related work include the Office of Naval Research (ONR), the Army Research Office, and the Air Force Office of Scientific Research (AFOSR). In an ONR notice posted on June 17, 2004, seeking grant proposals from universities, the topics listed included water-based photobiological production of hydrogen fuel. Over the past 15 years, the U.S. Army's National Automotive Center in Warren, MI, has sponsored fuel cell development for bus and truck applications, including auxiliary power units.

Other Federal Agencies

The U.S. Department of Transportation provides a small amount of funding that directly contributes to achieving the goals of the President's Hydrogen Fuel Initiative. Other federal agencies also fund hydrogen-related R&D. The Office of Science and Technology Policy leads a Hydrogen R&D Interagency Task Force, which provides a means for collaboration among nine agencies. The task force has established subgroups to develop and carry out an interagency coordination plan. Topics for collaboration include materials, electrochemistry, advanced

hydrogen production methods, development of components and manufacturing technologies, demonstration of systems and end-use applications, and development of safety codes and interface standards.

U.S. Government Laboratories

A significant portion of the government's resources for hydrogen related R&D is used to fund work at government-owned national laboratories. Some of these labs are government-operated, but most are operated by contractors to accomplish government missions and objectives. Substantial DOE funded hydrogen and fuel cell R&D is done by researchers at the Department's major laboratories, including:

- Argonne National Laboratory
- Idaho National Engineering Laboratory
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- National Energy Technology Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories.

Tables from DOE's budget request for FY05 indicate that it plans to spend nearly $74 million on hydrogen and fuel cell R&D at these laboratories. Of this amount, $30 million is planned for hydrogen related work other than on fuel cells.

The National Renewable Energy Laboratory (NREL) is responsible for a major part of the hydrogen R&D conducted at, or managed by, DOE's national laboratories. NREL's R&D efforts are focused on hydrogen production and delivery, hydrogen storage, fuel cells, technology validation, safety, codes and standards, and analysis. Its primary goal is to help industry develop technologies to produce, store, transport, and use hydrogen made from renewable resources. In the area of production and delivery, the following projects are being carried out.

- Biological water splitting
- Photoelectrochemical water splitting

- Reforming of biomass and wastes
- Solar thermal water splitting
- Renewable electrolysis.

With respect to hydrogen storage, NREL researchers are investigating properties of materials that could enable DOE to achieve storage goals.

Important research is also conducted at, and managed by, DoD laboratories. The DoD laboratory system is managed and operated largely by the individual services. DoD is the largest federal sponsor of R&D, with an FY05 R&D budget request of $70.3 billion. About $13.6 billion of this amount is for basic research, applied research, and advanced technology development, the categories within which any hydrogen and fuel cell-related funding is located. The remaining categories focus on development and testing of specific weapon systems. The amount appropriated for basic and applied research in FY05 is $6.3 billion. About 39 percent of the work supported by these funds is performed by DoD laboratories, while 32 percent is performed by industry. Twenty-five percent of DoD's basic and applied research is accomplished at universities and colleges.

State Governments

The primary sources of government funding for hydrogen and fuel cell R&D in the U.S. are federal agencies, particularly the DOE. However, state governments have assumed a significant, and increasingly active, role.

The most aggressive state, with the most visible activities, is California. In their white paper published in July 2004,[19] authors from the University of California claim that California is a unique location for clean energy technology development. Thirty-four million people drive 23 million automobiles in the state, and it continues to experience significant air quality challenges.

The white paper also points out that California has been a leader in experimenting with alternative fuels, including those from renewable sources. The state pioneered "zero emissions vehicle" regulations. The California Fuel Cell Partnership (CaFCP), a public-private consortium, was created in 1999. This consortium has had a key role in bringing about the largest concentration of fuel cell vehicles in the world. It has funded analytical work, produced a variety of educational materials on hydrogen and fuel cells, conducted safety training, and contributed to construction of hydrogen refueling sites.

In April 2004, Governor Schwarzenegger announced his intent to create a "California Hydrogen Highway Network." This initiative is intended to stimulate development of hydrogen infrastructure throughout California, thus helping to

[19] Source: *An Integrated Hydrogen Vision for California,* White Paper/Guidance Document, Prepared with Support from the Steven and Michele Kirsch Foundation, July 9, 2004.

remove a key barrier to introduction of hydrogen-powered vehicles. A "California Hydrogen Economy Blueprint Plan" is to be developed by January 1, 2005. Five topic teams have been established to provide inputs for the plan, covering the areas of implementation, economy, blueprint and timeline, societal benefits, and public education. Team members include leaders from industry, government, and academia.

In specific recommendations for the Hydrogen Highway project, the California Fuel Cell Partnership has included an example map of a hydrogen refueling infrastructure in 2012. Its initial thoughts on a phased rollout envision 75 to 125 refueling sites, fueling about 25 vehicles per site. The CaFCP forecasts that there will be up to 300 fuel cell vehicles in California by 2008. Its view of the potential growth is that up to 8 times that number is possible by 2012. It notes that this accomplishment will depend on technology advances, and assumes "that cost reduction efforts have been successful." Fuel cell buses, stationary fuel cell power units, and fuel cell auxiliary power units (APUs) for long-haul trucks could increase the demand for hydrogen, thus encouraging hydrogen infrastructure development.

Those responsible for policy, air quality rules, and other regulations in California are aware of the linkage between their decisions and the potential for investment in hydrogen-related technology. During our meetings with California officials, the policy support for low emission distributed power generation was mentioned. The California Air Resources Board has published regulations on distributed generation (DG). These impose the requirement that emissions from DG power plants may be no greater than emissions allowed for central power plants. DG facilities powered by fuel cells are deemed to meet the requirement. California has also instituted new rules limiting idling by trucks to 5 minutes. This rule should encourage development of low-emission APUs.

During our discussions with California government and industry leaders, individuals noted that success in achieving stationary use of hydrogen is viewed as a precursor to success in using hydrogen for vehicles. The state has created a California Stationary Fuel Cell Collaborative, a joint initiative of federal, state, and nongovernmental organizations promoting stationary fuel cell commercialization. Its website indicates that it will take specific actions to promote a variety of fuel cell technologies, sizes, and applications for installation in California. It envisions the state as a critical market for the fuel cell industry. DoD, DOE, and the US EPA are among the members of the Collaborative.

Other states providing support for hydrogen development include New York, Michigan, Florida, Ohio, and Hawaii. Last year, the New York State Energy Research and Development Authority, in collaboration with the Long Island Power Authority and the New York Power Authority, invited proposals for work to support the advancement of the hydrogen economy in New York State. Topics to be addressed in proposals included a hydrogen roadmap for the state; education and outreach activities; codes and standards review; and R&D in the areas of

hydrogen production, storage, distribution, and utilization. Supported by $750,000 in state funding, awards were announced in June 2004.

In April 2004, a Hydrogen Business Partnership was created to work with the state of Florida on strategies to commercialize hydrogen technologies. Earlier in the year, Florida's governor proposed a $15 million state program to demonstrate the latest advances in hydrogen energy technology as power sources for homes, businesses, and vehicles. Two years ago, Michigan's governor announced the state's NextEnergy Program. This initiative, with a proposed 3-year budget of $52 million, is administered by the Michigan Economic Development Corporation. It is intended to develop a state-of-the-art, full-service fuel cell and alternative energy industry in Michigan. At a DOE program review in May 2004, NextEnergy made a presentation on its plans for a Microgrid and Hydrogen Fueling Facility project, whose costs are being shared by NextEnergy and DOE.

The state of Hawaii, with a substantial military presence, has supported hydrogen-related activities since the mid-1980s.[20] The state's energy mix is dominated by petroleum, which accounts for 90 percent of total energy use and is the fuel used for power generation. It also has relatively high energy costs and isolated island-by-island grid systems. As a result, Hawaii is particularly interested in renewable energy sources and alternative fuels, including hydrogen. Given its unique circumstances among the states, Hawaii could be a location where hydrogen use becomes economically competitive before that occurs elsewhere.

The Hawaii Natural Energy Institute (HNEI) initiated a DOE-funded program on development of renewable energy production in 1986. In 1996, HNEI was named a DOE Center of Excellence for Hydrogen Research and Development. Current efforts include development of high-efficiency, low-cost technologies for direct water splitting using photoelectrochemical techniques, and the development of materials for on-board hydrogen storage. For work on hydrogen production, the University of Hawaii is partnering with industry, national laboratories, and other academic institutions.

The Office of Naval Research (ONR) is supporting some work in Hawaii. Using ONR funds, HNEI created the Hawaii Energy and Environmental Initiative in 2000. Development and testing of fuel cells, for both commercial and military applications, is being conducted by the partnership of HNEI and the Naval Research Laboratory. With funding of over $10 million for this jointly-sponsored activity, one key result has been establishment of the Hawaii Fuel Cell Test Facility. This facility, developed in conjunction with UTC Fuel Cells and the Hawaiian Electric Company, opened in April 2003. The facility enables testing under a wide range of fuel cell operating conditions.

Hawaii has a plan for energy diversification, and current leadership seems committed to moving forward. In July 2004, HNEI and Sentech completed a report on

[20] R. Rocheleau, E. Miller, et. al., *Hydrogen Programs in Hawaii*, at www.hnei.hawaii.edu/rocheleau_manuscript.pdf.

the potential for large-scale use of hydrogen, fuel cells, and renewable energy in Hawaii.[21] In 2002, a partnership meeting attended by DOE, DoD, industry, and local utilities was conducted to enhance focus and coordination. The Gateway Distributed Energy Resources Center on the island of Hawaii has just begun operation. Its purpose is to provide a focal point for developing hydrogen and distributed energy systems.

Public-private partnerships are important in the pursuit of Hawaii's energy goals. One partnership is the Hawaii Hydrogen Power Park, funded by DOE through the Hawaii State Energy Office. A recent activity of the Hawaii Center for Advanced Transportation Technologies has been the installation of a fuel cell/battery hybrid electric propulsion system into an Air Force bus. This is the first fuel cell vehicle in Hawaii. Another project has been proposed by a partnership among HNEI, ONR, the Navy, and the Hawaiian Electric Company. This project would demonstrate several commercial and developing solar photovoltaic technologies. If the project goes forward, the partners state that the site, on Ford Island at Pearl Harbor, would be appropriate for follow-on hydrogen activities.

Universities

Many universities have significant capability to make hydrogen-related technology advancements. The University of California has several activities devoted to hydrogen energy. Campuses at Davis and Irvine have notable programs. Texas A&M, the University of Hawaii, and the University of Miami are all making substantive contributions to the knowledge base in hydrogen energy.

Other Countries

Substantial commitments to hydrogen and fuel cell development are being made outside the U.S., particularly in Europe and Japan. The resources devoted each year by Japan to fuel cell and hydrogen technology research, development, and demonstration have tripled since 1995. Last year, the European Commission announced a 2.1 billion euro initiative for hydrogen, fuel cells, and related renewable energy activities. The International Energy Agency (IEA) Hydrogen Implementing Agreement has several ongoing projects which reflect international concurrence on R&D. A recent report on this cooperation reflects the progress and accomplishments made, mostly in systems studies.

In response to an initiative led by the U.S., representatives of 15 countries and the European Commission gathered in Washington, DC, for a November 2003 ministerial meeting on hydrogen. Each signed a document creating the International Partnership for the Hydrogen Economy (IPHE). Its stated purpose is to "organize and implement effective, efficient, and focused international research, development, demonstration and commercial utilization activities related to hydrogen and

[21] *Nurturing a Clean Energy Future in Hawaii: Assessing the Feasibility of the Large-Scale Utilization of Hydrogen and Fuel Cells in Hawaii*, Hawaii Natural Energy Institute and Sentech, July 2004.

fuel cell technologies." Governments represented on the steering committee are Australia, Brazil, Canada, China, France, Germany, Iceland, India, Italy, Japan, Norway, South Korea, Russia, the United Kingdom, and the United States.

Iceland has been particularly visible in making a commitment to establishing an energy economy based on hydrogen. It co-chairs the IPHE's Implementation and Liaison Committee. Its government and industry are aggressively planning for hydrogen and taking a leadership role in installation of hydrogen-related technologies. A government/industry joint venture, Icelandic New Energy, was established in 1999. Its mission is to "investigate the potential for eventually replacing the use of fossil fuels in Iceland with hydrogen and create the world's first hydrogen economy." Minority partners from industry include Shell Hydrogen, DaimlerChrysler and Norsk Hydro.

Projects planned for Iceland include demonstration of fuel cell buses, passenger vehicles, and fishing vessels. A hydrogen station in Reykjavik opened in April 2003. Hydrogen is produced by an on-site electrolyzer. In the future, plans are that hydrogen production will use electricity made from the island's plentiful supplies of geothermal energy, augmented by hydropower and solar generation.

The Naval Air Station at Keflavik is host command for the North Atlantic Treaty Organization (NATO) base in Iceland, and a number of major commands are located there. In view of this fact and the country's commitment to hydrogen technology, Iceland could be a desirable site for DoD planners to gain experience with hydrogen as a fuel for its facilities and ground vehicles.

Technology Goals

The successful transition to a 'hydrogen economy' will require integration of the various activities undertaken to address the many barriers. To help manage these activities, goals must be established and progress in achieving them monitored.

U.S. Department of Energy

The President's Hydrogen Fuel Initiative is intended to accelerate the pace of R&D on the hydrogen production and distribution infrastructure needed to ultimately support hydrogen powered fuel cells for transportation. With full funding and successful achievement of technology and cost goals, the program is expected to facilitate industry commercialization decisions by 2015. A decision at that time to produce fuel cell vehicles for consumers would result in vehicles available for sale by about 2020. This would enable market penetration leading to significant oil displacement and environmental benefits in 2030 and beyond.

Detailed goals and milestones for the President's Hydrogen Fuel Initiative are found in various DOE documents. One summary schedule, included here (Figure 3-5), is taken from the DOE *Hydrogen Posture Plan*.[22] The milestones shown are

[22] U.S. Department of Energy, *Hydrogen Posture Plan*, February 2004.

associated with the key activities of DOE's hydrogen program, through completion of the critical path technology development phase in 2015.

Figure 3-5. Hydrogen R&D Milestones

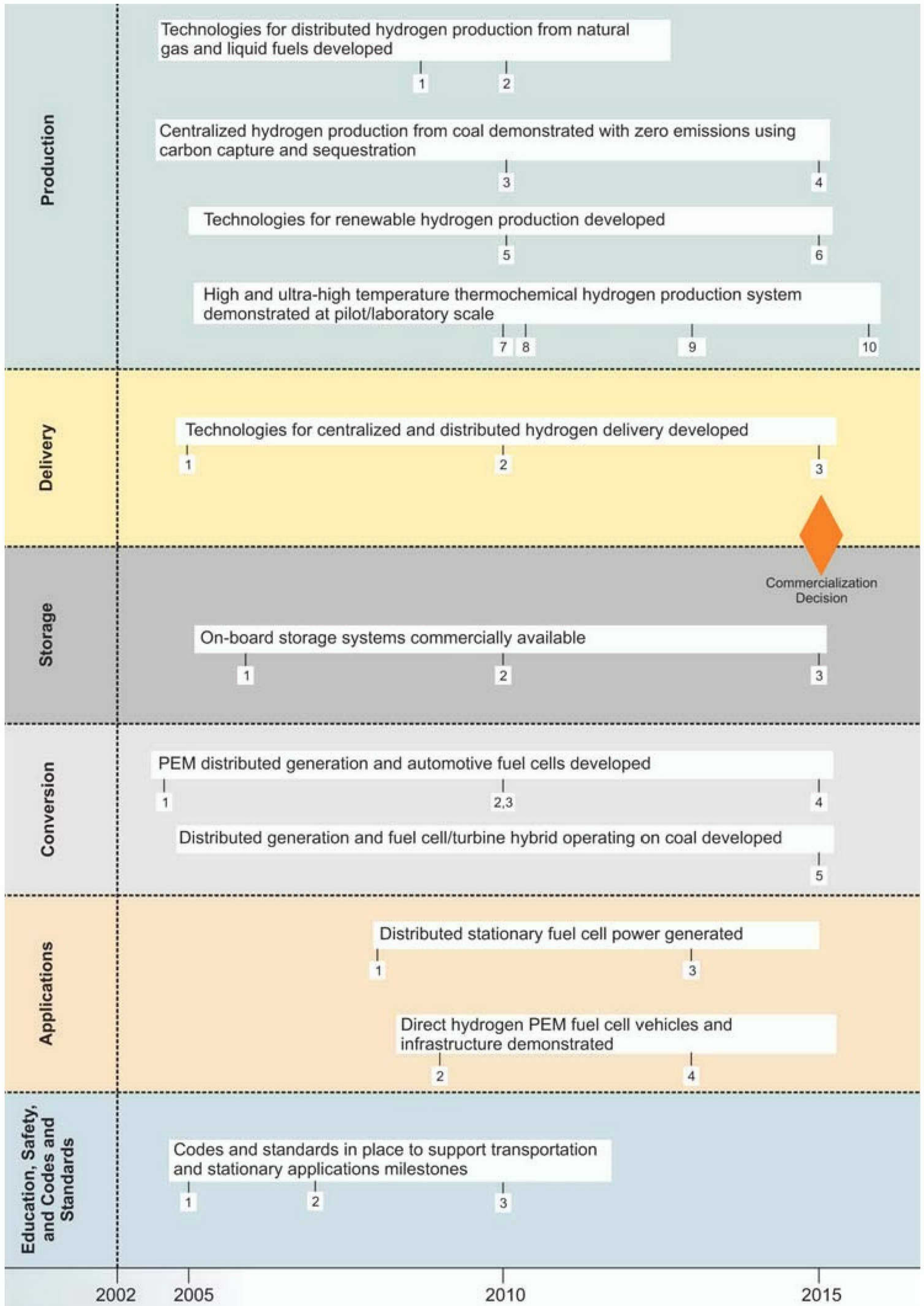


Figure 3-5. Hydrogen R&D Milestones (Continued)

Production Milestones

Distributed Natural Gas/ Liquid Fuels*

1. 2009: Develop technology to produce distributed hydrogen from natural gas or liquid fuels at a refueling station that projects to a cost of $2.50/gge for hydrogen. [At the pump, untaxed, no carbon sequestration]
2. 2010: Develop technology to produce hydrogen from natural gas or liquid fuels at a refueling station that projects to a cost of $1.50/gge for hydrogen. [At the pump, untaxed, no carbon sequestration, at 5000 psig]

Central Coal*

3. 2010: Develop pilot scale membrane separation and reactive/membrane separation technology for hydrogen production that meets cost targets.
4. 2015: Demonstrate a zero emission coal plant producing hydrogen and power with carbon capture and sequestration at a 25% cost reduction that projects to $0.80/gge at the plant gate ($1.80/gge delivered).

Renewable Resources

5. 2010: Develop technologies for integrated wind hydrogen production at $2.85/gge delivered assuming a 500 gge/day electrolyzer system and $0.04/kWh wind electricity (2015: $2.25/gge).
6. 2015: Demonstrate laboratory-scale biological system to produce hydrogen at a cost that projects to $10/gge at the plant gate ($11/gge delivered). Demonstrate laboratory-scale photoelectrochemical water splitting at a cost that projects to $5/gge at the plant gate ($6/gge delivered). The long term goal for these hydrogen production technologies is to be competitive with gasoline.

High-Temperature Thermochemical

7. 2010: Laboratory-scale demonstration of ultra-high-temperature thermochemical hydrogen production from solar reactors that project to a cost of $2.50/gge ($3.80/gge delivered).
8. 2011: Pilot-scale demonstration of high-temperature thermo-chemical production for use with nuclear reactors that projects to a cost of $2.50/gge ($3.50/gge delivered).
9. 2013: Design of engineering scale nuclear hydrogen production system completed.
10. 2017: Engineering-scale demonstration of thermochemical hydrogen production system with cost that projects to less than $2.00/gge at the plant gate ($3/gge delivered) using heat from nuclear reactors.

Storage Milestones

1. 2006: Downselect hydrogen storage options with potential to meet 2010 targets.
2. 2010: Develop and verify on-board storage systems achieving: 6% by weight capacity and 1500 watt hours/liter energy density at a cost of $4.00/kWh of stored energy.
3. 2015: Develop and verify on-board storage systems achieving: 9% by weight capacity, 2700 watt hours/liter, and $2.00/kWh.

Applications Milestones

1. 2008: Validate first regional networks with fuel cell systems that project a cost of less than $1,250/kW.
2. 2009: Direct hydrogen polymer electrolyte membrane fuel cell vehicles demonstrated at multiple sites, achieving 2,000 hours durability.
3. 2013: Validate stationary fuel cell system that co-produces hydrogen and electricity at 40,000 hours durability with 40% efficiency at a cost of $750/kW or less.
4. 2013: Validate direct hydrogen polymer electrolyte membrane fuel cell vehicles achieving 5,000 hours durability (service life of vehicle) and 300 mile range.

Phase 1 Commercialization Decision: 2015

Based on technology development success in meeting customer requirements and establishing a business case.

Conversion Milestones

1. 2004: On-board fuel processing Go/No Go decision based on ability to achieve 78% efficiency and <0.5 minute start time.
2. 2010: Distributed stationary generation natural gas/propane 50-250 kW fuel cell developed: 40% electrical efficiency, 40,000 hours durability (equivalent to service life between major overhauls), at a cost of less than $400-$750/kW.
3. 2010: Develop direct hydrogen polymer electrolyte membrane automotive fuel cell operating at 60% peak efficiency, 220 W/L density, 325 W/gge specific power at a cost of $45/kW (automotive production quantity).
4. 2015: Polymer electrolyte membrane automotive fuel cell meets cost of $30/kW.
5. 2015: Fuel cell/turbine hybrid operating on coal developed at a cost of $400/kW with a system efficiency of 70% with carbon sequestration.

Education, Safety, and Codes and Standards Milestones

1. 2005: Publish codes and standards models and safety and training materials.
2. 2007: Education program on safety in place.
3. 2010: Technical codes and standards in place to support regulatory standards.

Delivery Milestones

1. 2005: Define a cost-effective hydrogen fuel delivery infrastructure for supporting the introduction and long-term use of hydrogen for transportation and stationary power.
2. 2010: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.30/gge of hydrogen.
3. 2015: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen.

* *The assumed feedstock cost for natural gas is $4.00/million Btu and the assumed cost for coal is $29.00/short ton.*

Source: DOE Hydrogen Posture Plan.

U.S. Department of Defense

As indicated in the previous section, DoD research organizations sponsor, manage, and perform R&D costing over $5 billion annually. A review of programs and projects managed by the following organizations indicates that a very small portion of this work is related to hydrogen and fuel cells:

- U.S. Army Engineer Research and Development Center (ERDC)/Construction Engineering Research Laboratory (CERL)
- Army Research Office
- U.S. Army National Automotive Center (NAC)
- Air Force Research Laboratory (AFRL)/Air Force Office of Scientific Research (AFOSR)
- Office of Naval Research (ONR)
- Naval Research Laboratory
- Defense Advanced Research Projects Agency (DARPA).

While each of the services manages some fuel cell research, development, and/or demonstration activities, we did not find any department- or service-wide goals. Goals have generally been set for individual projects. For example, a stationary fuel cell demonstration located at the Watervliet Arsenal in New York has been evaluated by ERDC. Its goals included fuel cell availability for providing electricity to family housing units. NAC has supported, along with industry and university partners, development and demonstration of reformer-based, liquid-fueled auxiliary power units for military and commercial use. ONR is funding development of a method to extract hydrogen from diesel fuel, for use in a fuel cell system. This 500 kW reformer, compatible with a PEM fuel cell, was tested at DOE's Idaho National Engineering Laboratory. ONR is also one of the performers of R&D for a portable fuel cell power system for soldiers. Its goals are related to improving performance and cost relative to batteries.

U.S. Industry

Completion of commercialization of hydrogen is the primary goal of the industrial sector. Product engineering, configuration control, and reliability testing have been the principal activities of industry. The current gaps in these activities are in integration equipment (including connectors), safety equipment (including hydrogen-specific sensors), and liquefaction (cryocoolers). Most companies remain focused on their individual product technologies, and few have engaged successfully in a purposeful integration role. The hydrogen energy sector lacks the market pull necessary to provide the resources to address the need for a new

generation of connectors and sensors. Liquefaction lags behind because of a perception of difficulty regarding the balance of plant complexity in cryosystems.

Integration is necessary to establish a validation venue for the hydrogen energy chain. A tier of integrators is expected to emerge within certain applications (such as uninterruptible power supplies) with the introduction of technologies such as the Plug Power 5 kW and the Ballard 1 kW fuel cells.

Cost management in integration is a particular challenge facing stationary and vehicle systems today. This is an ongoing effort within the industry. Progress has been notable in the establishment of hydrogen fueling stations. More than 50 stations will be completed in the U.S. by the close of 2004.

HYDROGEN COMMERCIALIZATION POTENTIAL

This section provides a perspective on commercialization possibilities that could result from successful hydrogen RD&D during the next two decades. We first discuss commercial expectations with respect to initial applications for hydrogen-related technology, and then the higher volume applications which could occur later.

Initial Commercial Applications

Some potential exists for using small amounts of hydrogen in the near-term—that is, by 2015.

STATIONARY

The small (10 kW) generator replacement is an early target for the SOFC commercially. Large-scale PEM fuel cells using direct hydrogen are being developed by companies such as United Technologies and Fuel Cell Energy. An interesting adaptation is the placement of GM's fuel cell engine in a stationary application at a Dow Chemical plant. Small stationary uses of PEM cells are achievable today in 5 kW increments using the fuel cells produced by Plug Power and other companies. By 2015, these could be competitive in selected applications, such as for uninterruptible backup power.

Any PEM fuel cell requires pure hydrogen; thus the supply issue must be addressed. Consideration of potential fuel cell applications must also take into account the market price instability of using natural gas, methanol, or other complex feedstock.

MOBILE

During the past few years, a number of organizations have made statements regarding expectations and intentions with regard to commercialization of hydrogen-using propulsion systems in vehicles. Among the most visible of these

organizations have been major multinational vehicle manufacturers. Some of these statements imply commercialization dates as early as 2010. Given the daunting technological challenges that remain, however, commercial use of hydrogen for automobiles and light trucks is not likely until at least 2015.

We believe that the first hydrogen fuel cells will be used in a variety of other mobile applications before they are available for consumers of personal-use transportation. While these other applications account for a relatively small amount of energy consumption, their duty cycles and other characteristics are such that the requirements of fuel cell cost, durability, and performance are not as demanding. With continued development success resulting from programs sponsored by government and industry, fuel cells could be a viable propulsion alternative a bit earlier than 2015 for vehicles such as:

- Materials handling equipment, such as forklifts
- Ground support equipment, such as at airports
- Package delivery trucks
- Maintenance equipment, such as mowing machines.

Significant work has been conducted on fuel cells for transit buses. Such buses are being demonstrated in Europe and the U.S. However, the costs still exceed $2 million per bus, which is nearly 10 times the cost of a conventional bus. While we expect bus applications to be cost-competitive before automobile applications, it is not likely that they will be competitive with conventionally fueled, natural gas, biodiesel, or hybrid-electric buses before 2015.

The introduction of any fuel cell vehicles will depend on the availability of cost-competitive hydrogen. One characteristic of the vehicles considered first for fuel cell use is that they can be efficiently refueled at the same central location each time fueling is required. However, additional work is needed, as described earlier, to achieve the hydrogen-related goals, such as those established by DOE and its industry partners. We believe it is possible that there could be some sites at which hydrogen may be a viable fuel alternative after 2012. However, very few locations are likely to have the right conditions to support hydrogen—without a substantial subsidy and/or other controversial policies—until at least 2015.

The use of fuel cells to power heavy truck auxiliary power units (APU) is a topic receiving attention, and presents another opportunity for early applications. One reason for this interest is the concern about emissions from the operation of 500- to 600-horsepower diesel engines just to provide truck cab air conditioning or heat. California intends to begin enforcing limits on truck idling, which should provide an incentive for development of APU technology. Unless development of liquid fuel reformer technology is successful, however, hydrogen storage and availability will continue to be deterrents to this application. Once technical issues

have been resolved, fuel cell economics will favor their introduction in APUs before commercialization in high-volume production light vehicles.

High-Volume Commercial Applications

In the mid-term, between 2015 and 2035, the potential exists for introduction of hydrogen fuel in high-volume applications.

STATIONARY

The development of fuel cells as generator replacements is progressing. Both low-temperature PEM fuel cells and high-temperature alternatives such as solid oxide technologies are succeeding to the extent that companies are tooling for production capability.

In the U.S., Plug Power is recognized for its 5 kW PEM generator factory, and General Motors is adapting its larger power PEM “engines” for industrial stationary power. Westinghouse, under the DOE SECA program, is establishing a solid oxide generator that has garnered pre-production quantity orders, including a recent award of 10 systems from California’s South Coast Air Quality Management District. The U.S. Army program managed by CERL used phosphoric acid fuel cell technology to gain operational experience. United Technologies, the supplier, has said it would offer these 250 kW devices for commercial applications.

With continued progress, the stage could be set for increasing fuel cell production of electricity at stationary sites after 2015. Initially, this would occur at relatively small distributed generation plants. However, hydrogen fueling infrastructure and insufficient predictability in hydrogen fuel price are expected to inhibit growth. This explains why PEM fuel cell developers are seeking low hydrogen consumption missions such as backup uninterruptible power supply. The use of natural gas as a feedstock for high-temperature systems, such as solid oxide, is the likely pathway for large-scale adaptation.

MOBILE

Significant national benefits could be realized if hydrogen fuel displaces fossil fuels, specifically conventional petroleum, in mass-produced automobiles and light trucks. Displacement of oil by domestic fuels for transportation, and improved fuel economy, are required to reduce our nation’s dependency on vulnerable fuel supplies, which will be concentrated increasingly in the Middle East. If the sources of hydrogen are both domestic and pollution-free, then use of hydrogen can have additional benefits in reducing criteria pollutants and climate change emissions.

Among all applications for hydrogen, however, use in light vehicles is most tightly linked to achieving the DOE's stringent technical and cost development goals. In addition, commercialization will depend on the following:

- Major investment by industry in a hydrogen infrastructure
- Major investment by industry in production of fuel cells and related equipment
- Convenient refueling for millions of consumers
- Successful commercial introduction and widespread use of hydrogen fuel cells in stationary power applications, as well as centrally fueled fleet applications.

Therefore, we do not expect light-duty vehicles operating on hydrogen to be offered for sale for at least 12 years. More probably, 15 years or more will be required to reach this stage of development, even with very aggressive government-supported initiatives and policies.

EMISSIONS IMPACTS

Emissions reduction is one of the major benefits touted by advocates of a hydrogen-based energy economy. Users of hydrogen, including the military, expect that such emissions reduction benefits will be realized in their operations.

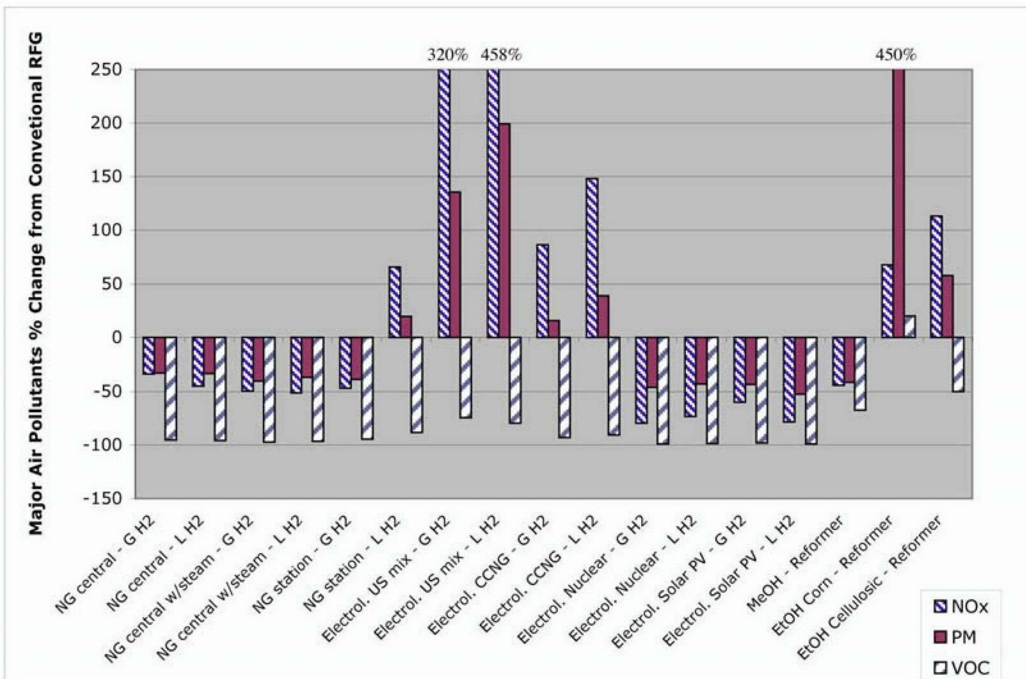
Hydrogen fuel cells used for power production will enable zero emissions of pollutants and carbon dioxide at the power generation site, if the hydrogen is produced off-site in a centralized facility. Distributed production of hydrogen on-site could result in emissions. The emissions amount in that case depends on feedstock (fossil fuel, biomass, solar, etc.) and the hydrogen production process (steam reforming, electrolysis, etc.). In the case of centralized hydrogen production, the emissions impact is also a function of feedstock and the production process, but emissions associated with transportation and delivery of the hydrogen must also be considered.

The bottom line is that emissions benefits, or detriments, cannot be known without a detailed understanding of the total system. We can only be assured of the benefit that hydrogen delivered to a site will have no emissions at that site when converted to energy in a fuel cell. Depending on the hydrogen production and distribution pathway, vehicle emissions could increase by as much as 80 percent compared to the level of emissions from conventional vehicles (using the U.S. average grid power mix to produce liquid hydrogen via electrolysis), and decrease

by as much as 100 percent (in other words, be completely eliminated) with biomass and some other renewable pathways.[23]

The DOE, its national laboratories, the National Academies, and others have done extensive analysis to establish the link between emissions and hydrogen pathways. For example, DOE has supported work on the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Model by Argonne National Laboratory. Some results of applying that model are shown in Figure 3-6 and Figure 3-7.

Figure 3-6. Air Pollutant Emissions from Hydrogen Fuel Cell Vehicle Fueling Pathways



Source: *An Integrated Hydrogen Vision for California,* White Paper/Guidance Document, Prepared with Support from the Steven and Michele Kirsch Foundation, July 9, 2004.

Notes: GREET Model v1.6 (ANL, 2001). CCNG = combined natural gas power plant; EtOH = ethanol; G = gaseous; L = liquid; NG = natural gas; MeOH = methanol; PV = photovoltaics; RFG = reformulated gasoline.

To provide perspective, DOE has also supported some analysis of the potential macro impacts of using hydrogen. For example, with program success and the most optimistic scenarios, light-duty vehicle greenhouse gas emissions could be reduced by more than 500 million metric tons of carbon equivalent per year by 2040 using hydrogen fuel cell vehicles. That amount would reduce the projected 2040 carbon emissions from transportation by more than 75 percent.

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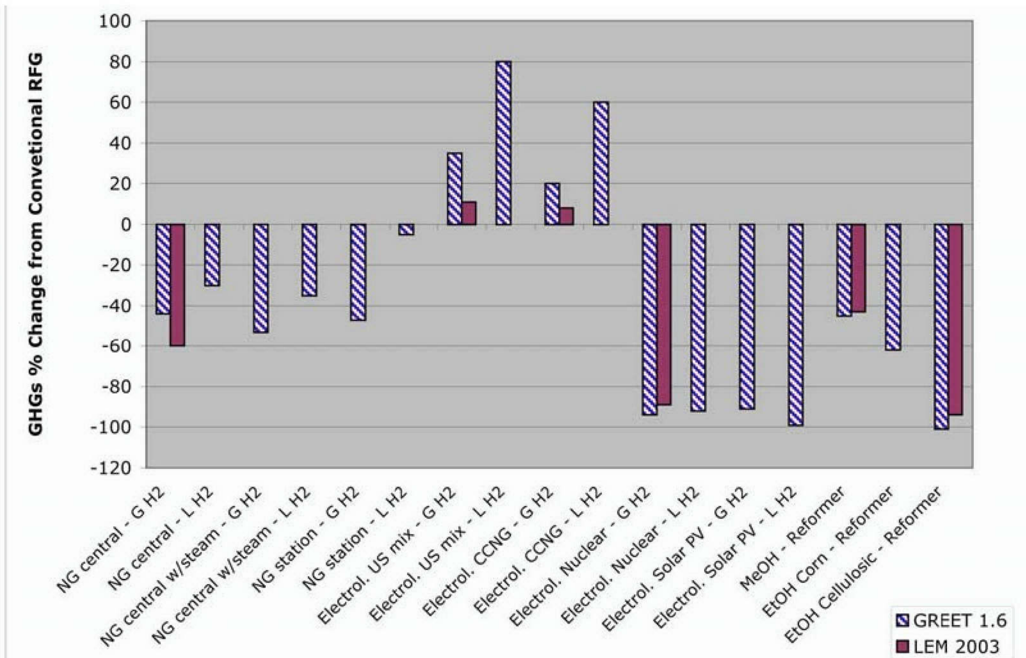
[23] *An Integrated Hydrogen Vision for California,* White Paper/Guidance Document, Prepared with Support from the Steven and Michele Kirsch Foundation, July 9, 2004.

DOE also states that, if 10 million tons of hydrogen per year were used to generate 150 billion kWh of the nation's electricity by 2020 (10 percent of the electricity projected to be added between now and 2020), 20 million tons per year of carbon dioxide emissions could be avoided. This assumes that the hydrogen is produced using renewable, nuclear, or fossil fuels with carbon capture and sequestration.[24]

Figure 3-7. Greenhouse Gas Emissions from Hydrogen Fuel Cell Vehicle Fueling Pathways



Source: *An Integrated Hydrogen Vision for California,* White Paper/Guidance Document, Prepared with Support from the Steven and Michele Kirsch Foundation, July 9, 2004.

Notes: GREET 1.6 is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. LEM 2003 is the Lifecycle Emission Model. CCNG = combined natural gas power plant; EtOH = ethanol; G = gaseous; L = liquid; NG = natural gas; MeOH = methanol; PV = photovoltaics; RFG = reformulated gasoline.

SUMMARY

Considerable effort is being expended to solve the complex barriers confronting more widespread use of hydrogen as a fuel. The decisions that ultimately result from the synthesis of these efforts will define future implementation pathways and benefits (cost and environmental). Future achievements will drive how and when hydrogen can be logically and practically introduced and used within DoD.

[24] U.S. Department of Energy, *Hydrogen Posture Plan*, February 2004.

Chapter 4

DoD Hydrogen Logistics and Applications

INTRODUCTION

The current achievements in fuel cell technology are the result of worldwide research and development by government and industry. Hydrogen and fuel cells offer the promise of abundant and clean energy. These technologies have near-term applications across a variety of stationary and mobile uses. As discussed in Chapter 3, the broader long-term success of hydrogen and fuel cell technologies depends on continued research and development to overcome the significant technical and cost barriers that remain.

The creation of an efficient supply chain linking hydrogen production to locations of hydrogen use is essential to realizing a hydrogen economy. This is a massive undertaking that would require the replacement of existing petroleum and natural gas infrastructure with hydrogen infrastructure over the long-term. A hydrogen energy chain for DoD has the additional challenge of needing to be deployable to any part of the world.

This chapter provides information on the logistics of hydrogen from the point of production to the point of use. Here we discuss the following:

- Current energy logistics supporting DoD
- Hydrogen volume and weight compared to current logistics fuels
- Hydrogen production, storage, distribution, and dispensing
- Military applications for hydrogen
- Hydrogen use at DoD facilities
- Hydrogen use in major weapon systems
- Battlespace hydrogen logistics.

DOD ENERGY LOGISTICS TODAY

Hydrogen proponents we interviewed outside DoD consistently recommended that DoD become more active in the development and demonstration of fuel cell technologies. This view was based to some degree on the perception that DoD produced most of the electricity and refined most of the finished petroleum

products it used. But that view is not entirely accurate: DoD purchases the vast majority of its electricity, all natural gas, and all refined petroleum from commercial suppliers. DoD is a consumer of energy, not a producer.

DoD competitively purchases grid electricity, natural gas, and petroleum, with delivery by commercial grid, pipelines, trucks, railcars, tankers, and barges. This results in the lowest purchase and delivery costs. DoD is able to competitively purchase energy worldwide because electricity, natural gas, and petroleum have over 100 years of development with worldwide specifications and infrastructure standards. These energy products are traded as commodities in open markets. DoD purchases fuel in 121 countries.

DoD prefers to utilize commercial bulk petroleum storage whenever possible. Storage tanks are leased from commercial terminals where needed to support distribution to specific military bases. Petroleum storage on base is usually owned and operated by the military service. However, there is a recent trend to contract with commercial firms to construct, operate, and maintain super stations for ground fuels on military bases. Bulk petroleum on and off base is stored in cylindrical tanks that routinely hold 20,000 barrels (840,000 gallons) or more.

Expeditionary forces use large rubberized fabric bags, rubber hoses, and portable pumps to create million-gallon "bag farms" where commercial petroleum infrastructure does not exist. These bag farms are light in weight and easily deployed by military engineering petroleum units. Initial operational status can be established in a matter of hours, with additional capacity set up as needed.

Petroleum, especially high-quality distillates like JP8 jet fuel and F76 fuel oil, now accounts for almost all of DoD's combat mobility fuel. Gasoline is primarily used for commercially acquired light-duty administrative vehicles. Heavier distillates are used for heavy-duty vehicles and heating. Residual fuel oils are used for limited power and steam generation, as well as propulsion of many Military Sealift Command ships.

Petroleum for the Navy and Air Force accounts for over 90 percent of the fuel used by DoD.[1] Most of this fuel is used for propulsion of ships and aircraft. Navy ships and Air Force transport and combat aircraft are particularly dependent upon commercial refueling at international ports. Conversion of these major weapon systems to hydrogen will not be practical until reliable hydrogen refueling of ships and aircraft is available worldwide.

In addition to the environmental impacts, we are increasingly challenged by our dependence on petroleum for our modern economy. In a world of increasing demand and decreasing reserves for petroleum, there exist both current and future risks of availability and cost that could dramatically degrade DoD's capability to field a combat force. An Army task force reported that petroleum represents

[1] The Defense Science Board Task Force on Improving Fuel Efficiency on Weapons Platforms, *More Capable Warfighting Through Reduced Fuel Burden*, January 2001, page 4.

70 percent of the bulk tonnage needed to support a military force on the battlefield.[2] Reductions in petroleum use are viewed as a way to increase warfighting capability by reducing logistics requirements for fuel.

An Army 2010 vision goal calls for a 75 percent reduction in fuel requirements for a deployed force.[3] Nonetheless, the use of hydrogen as a broad replacement for petroleum is unlikely in the next few decades. This is because of the much larger volume of hydrogen needed to deliver the equivalent energy as petroleum. Petroleum over the near- and mid-term will remain the best source of energy available with sufficient energy density and ease of universal transport to support a mobile combat force.

HYDROGEN VERSUS JP8 FUEL: VOLUME AND WEIGHT

Hydrogen is an attractive fuel, because pound-for-pound it has 2.76 times the energy content of JP8.[4] Thus the *weight* of DoD fuel transports would be reduced by over 63 percent if hydrogen could be substituted pound-for-pound for JP8. This would go a long way toward achieving the Army 2010 goal of reducing fuel requirements by 75 percent, without any improvements in weapon systems efficiency. If hydrogen had the same energy content on a *volumetric* basis as JP8, the volume of fuel needed in the battlefield would similarly be reduced by 63 percent. Unfortunately, hydrogen's volumetric relationship with petroleum fuels is just the opposite: an amount of hydrogen with equivalent energy has a significantly higher volume than petroleum.

The volume of gaseous hydrogen needed, when pressurized to 5,000 pounds per square inch (psi), to provide the same energy as 1 gallon of JP8 would require the same storage volume as 10.3 gallons of JP8.[5] If compressed to 10,000 psi, 5.16 gallons of hydrogen storage volume would be required to provide the same energy as 1 gallon of JP8. Liquefied hydrogen, at -253ºC (-423ºF), has a better volumetric relationship—only 4.115 gallons of liquid hydrogen are needed to replace 1 gallon of JP8.

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[2] Dennis J. Wend, "21st Century Truck Initiative," National Automotive Command, Tank-Automotive & Armaments Command, presentation at the Automotive Research Center's 6th Annual Conference on Critical Technologies for Modeling and Simulation of Ground Vehicles, May 23, 2000, page 4. Accessed Online August 15, 2004. http://arc.engin.umich.edu/arc/events/archives/conference/conf00/wend.pdf.

[3] Ibid.

[4] J. Hilsenrath, *Tables of Thermodynamic and Transport Properties of Air, Argon, Carbon Dioxide, Carbon Monoxide, Hydrogen, Oxygen, and Steam,* New York, Pergamon Press, 1960 (gas law constant, R, equals 598.169 (psi * cm^3)/(g*K)).

[5] This and the remaining calculations use the lower heating value of JP8 (125,000 Btu per gallon) and the lower heating value of hydrogen (113,400 Btu per kilogram).

In addition to the gaseous and liquid phases, hydrogen can be stored and supplied using pressurized absorption in metallic alloys[6] and on or in carbon or other substrates.[7] These are called solid-state hydrogen carriers. The best solid-state hydrogen storage medium developed to date is sodium alanate ($NaAlH_4$), with an effective reversible storage capacity of 0.025 kilograms of hydrogen per liter of volume.[8] It currently takes 10 gallons of sodium alanate[9] to provide the hydrogen energy equivalent of 1 gallon of JP8. The weight of sodium alanate equivalent to 1 gallon of JP8 would be 69.1 pounds—10.3 times the weight of the JP8.

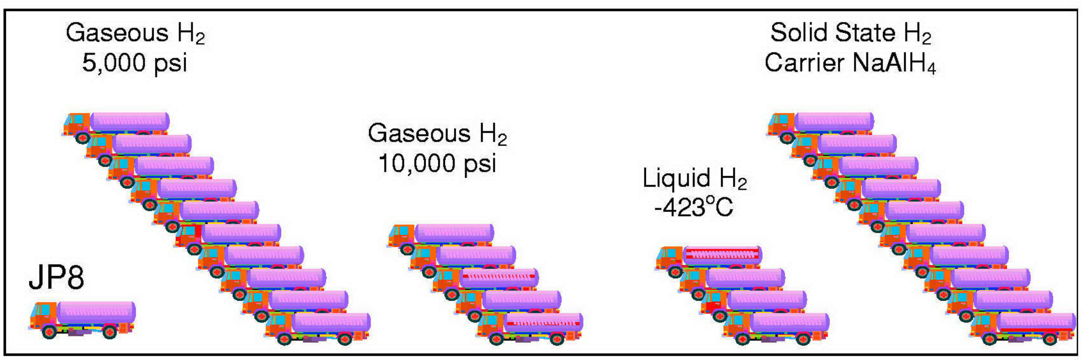
Table 4-1 and Figure 4-1 provide information on the relative volume efficiencies of hydrogen delivered in various physical states compared to JP8. Table 4-2 and Figure 4-2 provide information on the relative weight efficiencies of hydrogen in various physical states compared to JP8.

Table 4-1. Volume Relationships Between 1 Gallon of JP8 and Equivalent Energy Volumes of Hydrogen in Different States

	JP8	Gaseous hydrogen at 5,000 psi	Gaseous hydrogen at 10,000 psi	Liquid hydrogen at -253°C	Hydrogen absorption in metallic alloys[a]
Volume	0.1337 ft^3	1.38 ft^3	0.69 ft^3	0.5501 ft^3	1.337 ft^3
	1 gallon	10.3 gallons	5.16 gallons	4.115 gallons	10 gallons $NaAlH_4$ (U.S. dry)

[a] This is for today's sodium alanates.

Figure 4-1. Volumes of Equal Energy of JP8 and Hydrogen in Different Physical States



[6] Current materials are based on alanates, including sodium alanate, lithium alanate, magnesium alanate, and calcium alanate.

[7] Such substances include carbon nanotubes and other nanostructures, and chemical hydrides such as sodium borohydride and magnesium hydride.

[8] Department of Energy, Hydrogen, Fuel Cells & Infrastructure Technologies Program, personal communication, August 20, 2004.

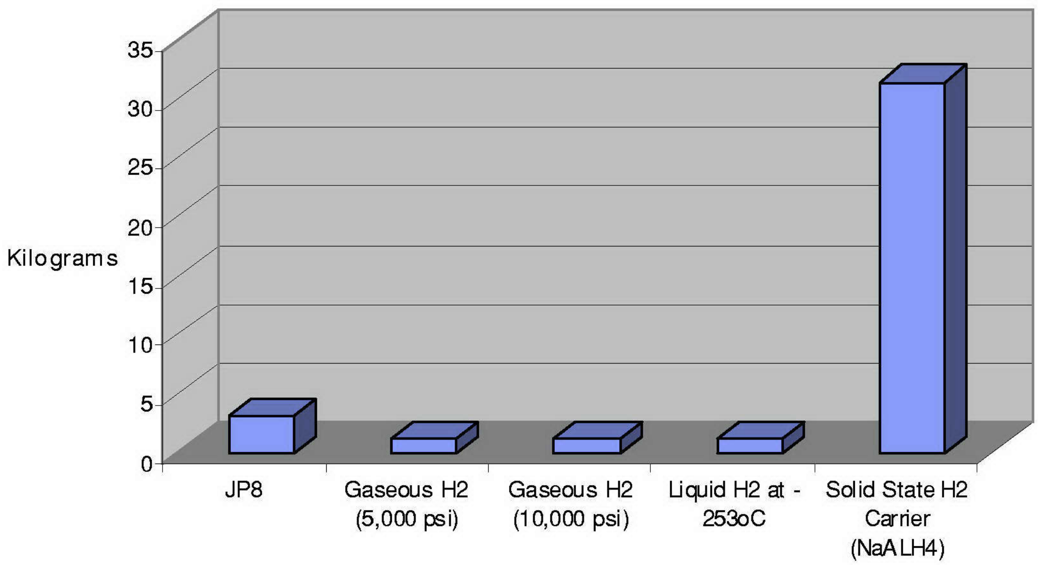
[9] Volume of sodium alanate is in dry U.S. gallons (1 liter = 0.227 dry U.S. gallon) since it is a solid.

Table 4-2. Weight Relationships Between 1 Gallon of JP8 and Equivalent Energy Volumes of Hydrogen in Different States

	JP8	Gaseous hydrogen at 5,000 psi	Gaseous hydrogen at 10,000 psi	Liquid hydrogen at -253°C	Hydrogen absorption in metallic alloys[a]
Weight	3.045 kg	1.1 kg H_2	1.1 kg H_2	1.1 kg H_2	31.343 kg $NaAlH_4$
	6.713 lbs	2.425 lbs	2.425 lbs	2.425 lbs	69.1 lbs $NaAlH_4$

[a] This is for today's sodium alanates.

Figure 4-2. Weight for Equal Amounts of Energy, JP8 versus Hydrogen



HYDROGEN PRODUCTION, DISTRIBUTION, STORAGE, AND DISPENSING

The DOE, the National Academies, members of academia, and industry have identified commercial options for the production, storage, and distribution of hydrogen. Capital markets are reluctant to invest in the commercialization of these competing technologies until demand is higher and the technologies are demonstrated. As in the automobile industry, which has tried every form of hydrogen and hydrogen storage available in demonstration fuel cell vehicles, we are likely to continue to see that a number of strategies will be tried and evaluated for producing, storing, distributing, and dispensing hydrogen before full consensus emerges for any particular technology.

DoD can create its own path at the risk of being out of step with the worldwide direction of the hydrogen industry. This is an appropriate approach where a significant force multiplier can be achieved independent of commercial hydrogen

production and distribution. However, the costs and risks must be balanced against tactical gains and the possibility that early DoD action could make eventual commercial supply to DoD more difficult. Development of a unique DoD infrastructure could also require the creation of unique distribution equipment not supported by commercial industry. Additional personnel, either hired or active duty, would be required to support such a DoD-specific application.

Popular reporting in the press on hydrogen often neglects to mention that a source of primary energy is needed to create hydrogen suitable for use in fuel cells, giving the public the false impression that hydrogen is freely available. Some of the primary energy sources also serve as sources for hydrogen. For example, natural gas, a hydrocarbon, can be reformed[10] into hydrogen. Reforming natural gas into hydrogen is arguably the most efficient and economical source of hydrogen today, achieving efficiencies of over 70 percent.[11,12]

Similarly, the challenges of distributing and storing hydrogen are misunderstood by the public at large, sometimes contributing to a misperception that the logistics of hydrogen will be easier than that of petroleum.

Centralized versus Distributed Production

Centralized production of hydrogen is similar to today's centralized refining of petroleum. A raw feedstock is mined and then shipped to a central production site for manufacturing. In the case of hydrogen, centralized production could use feedstocks such as natural gas, coal, biomass, or other hydrocarbons. Centralized production has the advantages of large economies of scale and the potential for carbon sequestration, which are lacking with distributed production. However, centralized production requires the ability to ship hydrogen from the point of production to the point of use.

Distributed production is envisioned to be the most economical method in the early stages of a transformation to a hydrogen economy. In distributed production, steam methane reforming or electrolysis would be used to create hydrogen at the site where it will be used or dispensed. This is how most stationary fuel cells get hydrogen today. Distributed hydrogen production is a good alternative for DoD

[10] Hydrogen production from natural gas commonly employs a process known as steam reforming. Steam reforming of natural gas involves two steps. The initial phase involves rendering the natural gas into hydrogen, carbon dioxide, and carbon monoxide. This breakdown of the natural gas is accomplished by exposing the natural gas to high-temperature steam. The second phase of steam reforming consists of creating additional hydrogen and carbon dioxide by utilizing the carbon monoxide created in the first phase. Online at http://www.fuelcellstore.com/information/generating_hydrogen.html, accessed August 14, 2004.

[11] National Research Council and National Academy of Engineering, *The Hydrogen Economy, Opportunities, Costs, Barriers, and R&D Needs,* The National Academies Press, Washington, DC, 2004, page 39 (Table 4-1).

[12] This also means that 30 percent of the primary energy is used to produce the hydrogen. There are additional energy efficiency penalties to compress or liquefy the hydrogen for more practical and economical distribution.

requirements because the transportation of hydrogen feed stocks is likely to remain easier than the transportation of hydrogen. The development of reformers capable of reforming existing logistics fuels (such as JP8) near the point of use, producing just enough hydrogen to support mission requirements, would seem especially advantageous to DoD. This would enable continued use of existing commercial petroleum infrastructure and its production, storage, and distribution efficiencies, while also providing hydrogen to high-value applications.

Although reforming petroleum to produce hydrogen is possible, significant issues with this technology are unresolved. The DOE funded research for over 10 years attempting to reform gasoline into hydrogen on-board vehicles. In August 2004 a program review concluded that, "based on the current state of the technology, it is unlikely that on-board [gasoline] processing will improve sufficiently to support the transition to a hydrogen economy."[13] DOE funding of on-board hydrocarbon reforming has been suspended.

The most significant challenge in reforming petroleum is the need to precondition hydrocarbon fuels to remove sulfur, since sulfur will poison catalysts used in proton exchange membrane fuel cells. The DESC states that the worldwide sulfur content of JP8 averages 0.05 percent by weight, or 500 ppm,[14] with total sulfur varying substantially by region. Hydrogen used in proton exchange membrane fuel cells must be 99.99 percent pure.

The Air Force Research Laboratory has successfully bench tested a miniature JP8 reformer and fuel cell that achieves an overall efficiency of 40 percent.[15] If this technology can be successfully scaled up and proves to be durable and reliable, significant barriers to the use of hydrogen by DoD combat forces might be eliminated. Current plans are to extend this technology to develop a viable diesel or JP8-powered fuel processing system for solid oxide fuel cell (SOFC) systems for military use that are more tolerant of sulfur and other contaminants than proton exchange membrane fuel cells. The present focus is on systems of up to 10 kW capacity. The emphasis is on full integration of the fuel processing system with the operational requirements of the SOFC stack.[16]

Steam methane (natural gas) reforming (SMR) is a well proven technology and is the primary method of producing hydrogen today. It is technologically possible for DoD to design, build, and preposition modular SMR plants ready for use

[13] "U.S. Department of Energy Decides to Discontinue On-Board Fuel Processor R&D for Fuel Cell Vehicles, Hydrogen, Fuel Cells & Infrastructure Technologies Program," U. S. Department of Energy, Energy Efficiency and Renewable Energy, accessed August 19, 2004. Online at http://www.eere.energy.gov/hydrogenandfuelcells/news_fuel_processor.html.

[14] Defense Energy Support Center, Product Technology and Standardization group, August 3, 2004.

[15] Reza Salavani et al., *Logistic Fuel Processor Development.* Air Force Research Laboratory, Materials & Manufacturing Directorate, Airbase Technologies Division, Tyndall AFB, FL. Report AFRL-ML-TY-TR-2004-4506, January 2004.

[16] Online at http://www.DoDfuelcell.com/research/rd_project4.html, accessed August 20, 2004.

where and when needed. In concept, small-scale plants producing up to 10,000 kilograms of hydrogen per day[17] could be established to support combat equipment requirements. In addition to the time needed to assemble the physical facility, a ready supply of natural gas and pure water is needed.

Unfortunately, neither natural gas nor pure water is evenly distributed on the planet. Based on information from the *Oil and Gas Journal* and *World Oil,*[18] the Energy Information Administration has compiled a list of countries with and without natural gas reserves, which shows 110 countries or major geographic regions that are without natural gas reserves.[19] Table 4-3 lists those countries. Even countries with natural gas reserves may not have natural gas where DoD might operate. In addition, small-scale SMR plants would require 3.4 to 3.7 gallons of purified water[20] for every JP8 gallon equivalent of hydrogen produced. Many locations with natural gas do not have adequate water resources to support SMR.

Because it is apparent that the required natural gas and water are not readily available everywhere that DoD operates or could operate, we believe that steam methane reforming is not a single point solution for the production of hydrogen in support of combat equipment.

Electrolysis of water is another option for producing hydrogen. Electrolysis depends on a source of pure water and electricity. Currently available commercial units require 60 kWh of electricity to produce a kilogram of hydrogen. For small distributed requirements,[21] electrolysis offers the ability to create hydrogen almost anywhere, provided sufficient electricity is available from other sources (such as solar, wind, petroleum powered generators or hydroelectric energy).

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[17] We base this concept on distributed onsite hydrogen production of natural gas using steam methane reforming using currently available technology. National Research Council and National Academy of Engineering, *The Hydrogen Economy,* page 179, Table E-35.

[18] Gulf Publishing Co., *World Oil,* Vol. 224, No.8 (August 2003), and PennWell Corporation, *Oil & Gas Journal,* Vol. 100, No. 52 (December 23, 2002).

[19] *International Energy Annual 2002,* Table 8.1, "World Crude Oil and Natural Gas Reserves, January 1, 2003," Energy Information Administration, Accessed online August 20, 2004, at http://www.eia.doe.gov/pub/international/iea2002/table81.xls.

[20] Water undergoes the following treatment to demineralize it to prevent scale in the boiler and contamination of catalysts: (1) chlorine removal using a carbon bed, (2) removal of minerals and scale-causing materials using a reverse osmosis system, and (3) "polishing" of water using a deionization resin bed to promote a longer unit life.

[21] Small distributed requirements are described in the National Academies report as being capable of producing 10 to 1,000 kg of hydrogen per day.

Table 4-3. Countries or Major Regions without Natural Gas Reserves

American Samoa	Grenada	Niue
Antarctica	Guadeloupe	Panama
Antigua and Barbuda	Guam	Paraguay
Armenia	Guinea	Portugal
Aruba	Guinea-Bissau	Puerto Rico
Bahamas, The	Guyana	Reunion
Belgium	Haiti	Saint Helena
Belize	Honduras	Saint Kitts and Nevis
Bermuda	Hong Kong	Saint Lucia
Bhutan	Iceland	Saint Pierre and Miquelon
Bosnia and Herzegovina	Jamaica	Saint Vincent/Grenadines
Botswana	Kenya	Samoa
Burkina Faso	Kiribati	Sao Tome and Principe
Burundi	Korea, North	Senegal
Cambodia	Korea, South	Seychelles
Cape Verde	Laos	Sierra Leone
Cayman Islands	Lebanon	Singapore
Central African Republic	Lesotho	Slovenia
Chad	Liberia	Solomon Islands
Comoros	Luxembourg	Sri Lanka
Cook Islands	Macau	Swaziland
Costa Rica	Macedonia	Sweden
Cyprus	Malawi	Switzerland
Djibouti	Maldives	Togo
Dominica	Mali	Tonga
Dominican Republic	Malta	Turks and Caicos Islands
El Salvador	Martinique	U.S. Pacific Islands
Eritrea	Mauritania	Uganda
Falkland Islands	Mauritius	Uruguay
Faroe Islands	Mongolia	Vanuatu
Fiji	Montserrat	Virgin Islands, U.S.
Finland	Nauru	Virgin Islands, British
French Guiana	Nepal	Wake Island
French Polynesia	Netherlands Antilles	Western Sahara
Gambia, The	New Caledonia	Zambia
Gibraltar	Nicaragua	Zimbabwe
Greenland	Niger	

Bulk Hydrogen Distribution

Bulk hydrogen can be distributed as a pressurized gas, cryogenic liquid or stored in a solid-state material. The modes used to transport the hydrogen from a centralized production point vary according to the physical state of the hydrogen and the quantity of hydrogen to be delivered over a period of time.

The energy needed to compress hydrogen to 5,000 psi is 4 to 8 percent of the hydrogen's energy content, depending on the starting pressure; to liquefy and store hydrogen requires 30 to 40 percent of its energy content.[22] This represents a significant energy loss that might make broad use of hydrogen as a logistics fuel unacceptable.

Pipelines used for the transmission of hydrogen would need to be at least 50 percent larger than current natural gas pipelines to achieve equivalent energy transmission rates. These pipelines would also need to be designed for the small size of the hydrogen molecule to avoid possibilities of leaking, and constructed of metals that resist hydrogen embrittlement.[23]

The DOE uses its NREL Optimization Model for the Analysis of Hydrogen Delivery to predict the costs of distribution based on a large number of data. Figure 4-3 displays one solution to the model, where the most economical mode of transport is shown based on the amount of hydrogen produced daily and the distance it must travel. The National Research Council and National Academy of Engineering addressed hydrogen distribution by stating:

> In any future hydrogen-based economy, key economic determinants [for the success of hydrogen] will be cost and safety of the fuel distribution system from the site of manufacture of the hydrogen to the end user. This is true of any fuel, but hydrogen presents unique challenges because of its high diffusivity, its extremely low density as a gas and liquid, and its broad flammability range relative to hydrocarbons and low-molecular-weight alcohols. These unique properties present special cost and safety obstacles at every step of distribution, from manufacture to, ultimately, on-board vehicle storage. Also critical is the form of hydrogen being shipped and stored. Hydrogen can be transported as a pressurized gas or a cryogenic liquid; it can be combined in an absorbing metallic alloy matrix or adsorbed on or in a substrate or transported in a chemical precursor from such as lithium, sodium metal, or chemical hydrides.[24]

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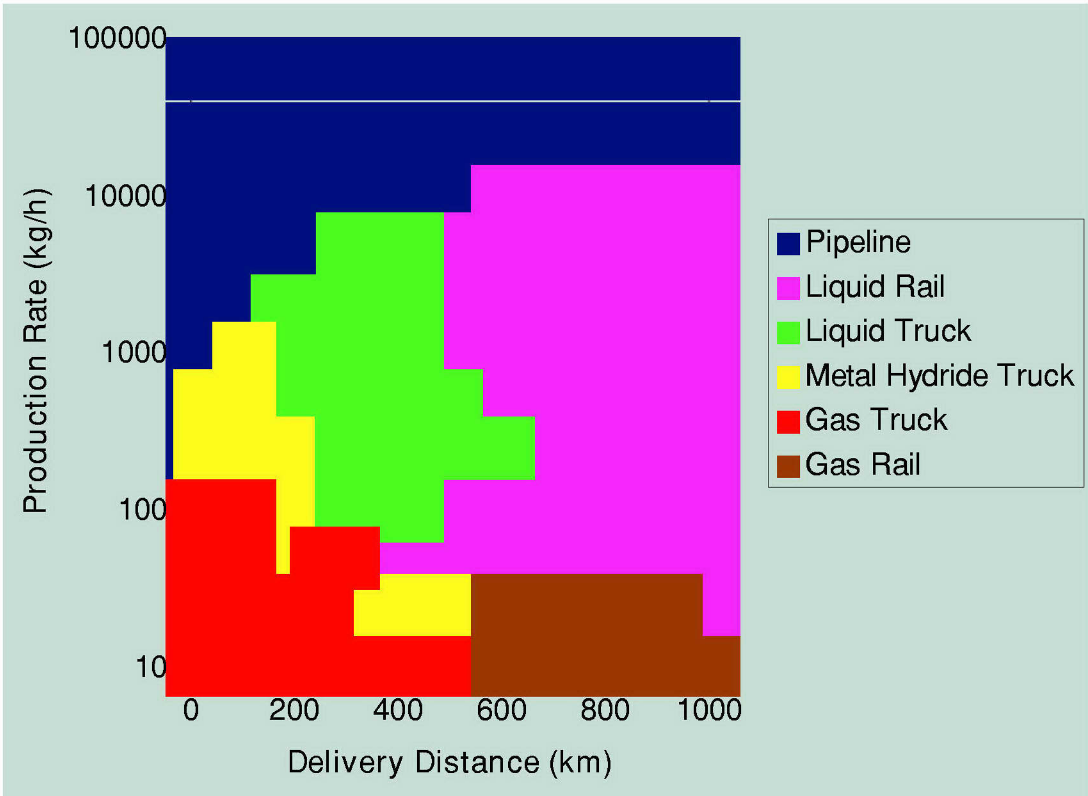
[22] National Research Council and National Academy of Engineering, *The Hydrogen Economy*, page 38.

[23] Ibid., page 39.

[24] Ibid., page 37.

Figure 4-3. Most Economical Hydrogen Transportation Mode for Different Production Rates and Delivery Distances



Source: National Renewable Energy Laboratory.

As previously noted, a majority of industrial hydrogen is produced and used within the fence line of the producing industrial facility (refineries, methanol production, ammonia production, and others). The rest is retailed[25] and distributed by pipeline to nearby users or by truck to both nearby and distant users.

However, it is important to examine bulk transportation of hydrogen, as it exists today, and how it might change in a future hydrogen economy. If, as the above quote suggests, hydrogen were to come into future widespread use as a primary replacement for petroleum, bulk distribution of this unique fuel would necessarily be much more commonplace than it is today. Projection of the methods of delivery of hydrogen is critical to the consideration at hand for DoD.

Liquefied hydrogen transport provides the most volumetrically efficient means of moving molecular hydrogen today. Tank trailers used to transport liquid hydrogen are similar in appearance and size to tank trailers that carry petroleum products. However, liquid hydrogen trailers are more expensive and complex. These trailers

[25] Joan M. Ogden, "Prospects for Large-scale Use of Hydrogen in Our Future Energy System," Testimony to the Committee on Science, U.S. House of Representatives, Washington, DC, March 5, 2003, page 5, online at http://www.house.gov/science/hearings/full03/mar05/ogden.htm, accessed August 20, 2004.

are very much like immense thermos bottles, with a ¾-inch stainless steel inner tank and a ¼-inch carbon steel outer tank.[26] The largest trailers can deliver up to 3,770 kilograms of liquid hydrogen, the energy equivalent of 3,420 gallons of JP8. Two and one-third of these large trailers of liquid hydrogen would be needed to replace one trailer of JP8 and deliver the same amount of energy to the user. Railcars can also be used to move liquid hydrogen. Transportation of liquid hydrogen over long distances requires management of hydrogen boil-off.

Gaseous hydrogen is primarily transported using pipelines and tube trailers but can also be moved by railcar. The gas industry uses pipelines to ship gaseous hydrogen to large industrial users such as refineries. Praxair Technology Inc. operates a 300-mile pipeline system on the Texas Gulf Coast. This is the longest hydrogen pipeline in the world,[27] but it is insignificant when compared with the 2.25 million miles of natural gas and petroleum pipelines in the United States.[28] Conversion of existing natural gas pipelines to hydrogen would be a difficult undertaking, because hydrogen would be three times as likely to leak as the larger methane (natural gas) molecules, and pipeline energy losses for hydrogen would be about three times greater.[29] In addition, existing pipelines are not designed to compress and pump hydrogen, nor to resist hydrogen metal embrittlement.

A major drawback to existing hydrogen pipelines from the DoD point of view is that they only support large industrial users. Hydrogen use across all economic sectors would need to expand dramatically to justify the investment of over $1 million per mile for a 12-inch pipeline to deliver hydrogen.[30] Expanding use of hydrogen by DoD is not currently sufficient to justify such large capital investment.

Construction of hydrogen pipelines to supply military bases is unlikely because of the remoteness of most military bases from current sources of hydrogen, high capital costs for pipeline construction, and pipeline transmission costs that are 1.5 to 3 times that of natural gas pipelines.[31] Use of hydrogen on DoD bases would need to increase substantially from near zero today in order to justify the placement of hydrogen pipelines for DoD's exclusive use. It is usually less expensive to bring the primary source of energy (for example, natural gas or coal) to a

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[26] *Safety Is the Goal for Hydrogen Transportation.* Air Products Community Advisory Panel (CAP), Pace, Florida. Online at http://www.pacecap.org/hydrogen.htm, accessed August 17, 2004.

[27] Information online at http://www.praxair.com, accessed August 18, 2004.

[28] *Country Analysis Briefs—United States of America*, Energy Information Administration. Online at http://www.eia.doe.gov/emeu/cabs/usa.html, accessed August 19, 2004.

[29] Timothy Coffey et al., *Hydrogen as a Fuel for DoD*, Defense Horizons, Center for Technology and National Security Policy, National Defense University, November 2003, page 2.

[30] Marianne Mintz et al., "Hydrogen Distribution Infrastructure," Argonne National Laboratory, Transportation Technology R&D Center, presentation made at the Jefferson Laboratory Fuel Cells Workshop, November 12, 2002. Online at http://www.jlab.org/hydrogen/talks/Mintz.pdf, accessed August 18, 2004.

[31] Ibid.

hydrogen plant located near the point of intended use than to transport hydrogen over long distances.

Tube trailers have the appearance of petroleum trailers except that instead of a single tank they have nine long high-pressure tubes that are stacked on the trailer. This is the least expensive and most practical way to deliver gaseous hydrogen today. Typical tube trailers have the capacity to deliver 330 kilograms of gaseous hydrogen. This is the energy equivalent of 300 gallons of JP8. In contrast, a typical petroleum tank trailer can carry 8,000 gallons of JP8. It would therefore take over 26 typical tube trailers of hydrogen to provide the same energy as a single 8,000-gallon delivery of JP8.

Solid-state hydrogen carriers are reversible and could provide much safer bulk and on-vehicle storage than technologies using gaseous or liquid hydrogen. There are perhaps hundreds of possible hydrogen storage options in these media, but no "serious contenders for the shipment [of hydrogen] from centralized manufacturing sites because they are inefficient on a weight and/or volume basis in comparison with cryogenic liquid hydrogen and pipeline-transmitted hydrogen."[32] Among the problem areas are "the overall weight of the storage alloys, the limited capacity of the alloys and carbon materials, the difficulties of liberating hydrogen from the carriers, and the high overall system costs."[33]

Solid-state hydrogen carriers would seem to be a perfect fit for military vehicles and equipment except for the high weight and volume penalty of these materials. As previously mentioned, the weight of sodium alanate equivalent to 1 gallon of JP8 would be 69.1 pounds, or 10.3 times the weight of the JP8. The Department of Energy's hydrogen research and development programs have a goal of increasing reversible solid-state storage capacity to 0.04–0.06 kilograms of hydrogen per liter of volume. If achieved, this would result in 4.2–6.3 gallons of solid-state material providing the equivalent energy of 1 gallon of JP8. Even with a potential doubling of vehicle efficiency, it seems unlikely that the military would consider reducing the weight of armaments and armor to accommodate the weight of solid-state hydrogen.

The need for large numbers of hydrogen delivery vehicles to support military operations could be mitigated by improving the efficiency of military equipment using fuel cells fueled by hydrogen. It is expected that light-duty fuel cell vehicles will have tank-to-wheels efficiency improvements that are approximately two to three times that of current internal combustion engines that operate at about

[32] National Research Council and National Academy of Engineering, *The Hydrogen Economy*, page 41.

[33] Ibid.

15 percent efficiency.[34] A doubling of military vehicle efficiency seems within the reach of current fuel cell technology.

All of the options for the distribution of molecular hydrogen present significant transportation issues that, at least at the current state of technology, limit the large-scale use of hydrogen on the battlefield. DoD's transportation requirements for fuel would rise significantly because the transport of hydrogen in all forms takes significantly more space than that of petroleum. For solid-state hydrogen storage technologies, the volume and weight are a factor of 10 higher. The impact of hydrogen on logistics, therefore, depends on how much hydrogen is needed, where it is produced, and what it is produced from.

Bulk Hydrogen Storage

Current options for the bulk storage of hydrogen are as a compressed gas, a cryogenic liquid, or as a solid-state material. Each has advantages and disadvantages, and all are currently more costly to store than liquid petroleum fuels. For example, storage of liquid hydrogen requires heavily insulated containers and careful management of boil-off by using the boiled off hydrogen or re-liquefying it. It is likely that all bulk hydrogen storage facilities will require greater setbacks from other buildings and structures than do similarly sized petroleum storage facilities.

Storage of compressed hydrogen requires the simplest technology, which is used for a wide range of gases. Storage vessels can be constructed in a variety of shapes and capacities. The chief limitation is the low storage density, although 10,000 psi storage approaches the energy density of liquid hydrogen. However, the higher cost of 10,000 psi systems might not justify their use when compared to the economics of 5,000 psi systems. Compressors may be needed to move gaseous hydrogen from the 3,125 psi of typical delivery vehicles to the working pressure of the storage facility. Filtration equipment may be necessary to ensure that any contamination (such as compressor oil) is removed from the hydrogen before storage or use.

A major concern with large storage vessels is the "cushion gas that remains in the empty vessel at the end of the discharge cycle."[35] In addition to aboveground storage vessels, a variety of concepts exist for storage of hydrogen underground in caverns or rock formations. Again, we emphasize that the volume and weight of the containers storing hydrogen would be significantly greater than the volume and weight of containers storing petroleum.

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[34] M.A .Weiss et al., *Comparative Assessment of Fuel Cell Cars,* Massachusetts Institute of Technology, Laboratory for Energy and the Environment, February 2003, Publication No. LFEE 2003-001 RP. Online at http://lfee.mit.edu/publications/PDF/LFEE_2003-001_RP.pdf, accessed August 19, 2004.

[35] Wade A. Amos, *Costs of Storing and Transporting Hydrogen,* National Renewable Energy Laboratory, Golden, CO, NREL/TP-570-25106, November 1998, page 13.

Most liquid hydrogen is stored in spherical tanks, because this shape has the least surface area for heat transfer per unit volume. As discussed previously in this chapter, liquid hydrogen provides the best energy-to-volume ratio of all currently available or developing storage methods. Its most obvious drawback is its extremely cold temperature, -253ºC (-423ºF). Even well managed liquid hydrogen storage experiences evaporation rates of 1 percent or more per day.[36] This does not present a problem provided hydrogen use equals or exceeds the evaporation rate of the bulk liquid hydrogen storage. Liquid hydrogen requires extreme care in handling, and personal protective clothing is an absolute necessity.

Metal hydrides are another bulk storage option. "Hydrides are unique because some can adsorb hydrogen at or below atmospheric pressure, then release the hydrogen at significantly higher pressures when heated—the higher the temperature, the higher the pressure."[37] Heat released during hydride formation must be continuously removed to achieve maximum hydrogen bonding. The hydride must then be heated to release the hydrogen. The major disadvantage of hydrides is that they store only 2 to 6 percent hydrogen by weight, and the heating and cooling requirements for hydrogen absorption and desorption must be closely managed to achieve maximum storage and recovery.

The selection of a storage method for hydrogen depends on consideration of the factors shown in Table 4-4.[38]

Table 4-4. Factors Affecting Choice of Hydrogen Storage Method

Factor	Issue
Application	◆ Is liquid hydrogen required? ◆ What pressure is required?
Required energy density	◆ What form of hydrogen delivery will be used? ◆ Is space an issue?
Quantity of hydrogen to be stored	◆ Is the storage used as a buffer, or primary storage for a large amount of hydrogen? ◆ What is the storage period? Will the storage be used to keep hydrogen for a few hours, or is it seasonal storage?
Readily available forms of energy	◆ Is there waste heat available? ◆ Is high-pressure steam available for a turbine to power a compressor? ◆ Can hydrogen be reliably produced on site?
Geology of the area	◆ Can it be used for underground hydrogen storage? ◆ Are there abandoned natural gas wells available?
Future expansion needs	◆ Are there reasons to believe additional storage will be needed in the future?

[36] Ibid., page 10.

[37] Ibid.

[38] Adapted from Amos, *Costs of Storing and Transporting Hydrogen,* page 24.

Table 4-4. Factors Affecting Choice of Hydrogen Storage Method (Continued)

Factor	Issue
Maintenance requirements	◆ Is high reliability required? ◆ How often can the storage system be shut down for maintenance? ◆ Liquefaction will have the highest maintenance requirements, followed by gaseous storage and finally metal hydrides.
Capital costs	◆ What are the capital costs? ◆ What are the capital costs of alternatives?

Based on current hydrogen storage technology, the following generalizations can be made regarding the choice of storage method:[39]

- Underground storage—For large quantities of gas or long-term storage (not applicable to DoD users)
- Liquid hydrogen—For large quantities of gas, long-term storage, low electricity costs, or applications requiring liquid hydrogen
- Compressed gas—For small quantities of gas, high cycle times, or short storage times
- Metal hydrides—For small quantities of gas.

Hydrogen Dispensing

In 2003 there were about 60 hydrogen refueling stations worldwide for experimental vehicles,[40] and new stations are opening worldwide on a regular basis. However, the companies and governments utilizing hydrogen vehicles are taking many different approaches to hydrogen vehicle refueling. The design of each station depends on the vehicles being supported, and as yet there are few standard designs. Each station is thus more expensive than if there were standard equipment and design.

Safety and construction standards are the subjects of great interest in the U.S. and overseas. Such standards are still in the early stages of development for hydrogen, and the DoD may benefit from participating in standards setting committees. DESC's current mission does not include the funding of alternative fuel

[39] Ibid., page 26.

[40] Joan M. Ogden, *Prospects for Large-scale Use of Hydrogen in Our Future Energy System*, Testimony to the Committee on Science, U.S. House of Representatives, Washington, DC, March 5, 2003, page 5. Online at http://www.house.gov/science/hearings/full03/mar05/ogden.htm 14, accessed August 20, 2004.

infrastructure for natural gas, propane, or ethanol vehicle refueling stations—or for hydrogen refueling stations.

MILITARY APPLICATIONS FOR HYDROGEN

As discussed previously, increasing use of hydrogen fuel for military applications will depend on RD&D resulting in advancements sufficient to stimulate private sector investment in the hydrogen energy chain. This section discusses our expectations about applications and timing relative to the use of hydrogen by DoD. We address the potential for hydrogen in applications at both permanent bases and forward bases.

The acquisition of new technology has evolved from DoD assuming all development risk, in order to acquire a custom solution, to one of procuring commercial off-the-shelf (COTS) equipment and militarizing it as necessary. The DoD goal of leveraging industry-led technology advancement is based on a desire to share risk and avoid long-term cost exposure. DoD's approach toward using hydrogen reflects this approach, but runs the risk that no potential militarization requirements are reflected in the emerging products. The result could be that when the DoD decides to use hydrogen fuel it could face unknown costs and delays in militarization of systems. One way to mitigate that risk is to maintain a DoD interface with industry to represent militarization requirements to designers, codes and standards developers, and regulators in order to embed militarization capability into enabling product technologies. For example, the development and use of a military design review standard would be important.

Permanent Bases and Installations

STATIONARY POWER

In facility operations where an uninterruptible power supply is required for computers, communications, hospital operations, or other purposes, there are feasible applications in the near-term (before 2015) for stand alone hydrogen energy. These applications can take advantage of a fuel cell system's ability to remain in active stand-by mode without being subject to deterioration via electrochemical discharge. In remote, off-grid applications where small amounts of power (10 kW or less) are required for short durations, the use of hydrogen fuel cells or hydrogen fueled internal combustion generators could also be economically feasible in the near-term.

These uses depend on reliable hydrogen supply scenarios, which can include on-site generation or palletized gas tank delivery. Sites that have water can use chemical hydrides to produce the hydrogen, since this material is easily deployable as bags of powder.

Fixed installations that have small, predictable electrical loads will likely be the first competitive military application for hydrogen energy. DoD and the military services should continue to support, and gain experience from, demonstrations of emerging hydrogen and fuel cell technologies. Doing so will help prepare for decisions on hydrogen fueled distributed generation systems that may become commercially competitive.

VEHICLE POWER

In the most optimistic scenario for commercial vehicles, hydrogen could be introduced for propulsion of ground support equipment and maintenance equipment between 2012 and 2015. Fuel cell versions of materials handling equipment, such as forklifts, towing equipment, and maintenance items such as mowers, are the vehicles most likely to be competitive within the next decade. The hydrogen would be supplied from a central fueling station on base and/or in an adjacent community. It is also possible that fuel cell auxiliary power units could be available, providing electricity for requirements other than propulsion, before 2015.

We do not expect that hydrogen fueled automobiles, trucks, or buses will be commercially available, for either military or civilian acquisition, before 2018. At that time, it could be possible for DoD to acquire hydrogen fueled non-tactical automobiles, light trucks, buses, and other vehicles for use in base operations and at training locations.

As with stationary power, DoD should seek opportunities to partner with others on hydrogen related development and demonstration projects involving vehicles. Relatively few demonstration projects are necessary to get the information required for sound decisions on the readiness and cost of hydrogen and fuel cell technologies. All efforts should be well coordinated within the department and among the services.

BENEFITS AND IMPACTS

In the near term, before 2015, we expect that the amount of hydrogen required by DoD will be less than 10 times the very small amount used by DoD today. This would serve the demands of the combination of stationary and vehicle applications.

After hydrogen fueled vehicles are commercially available, in the time frame of 2018 to 2020 at the earliest, the hydrogen demand by DoD could begin to increase more substantially from year to year. Since such a high percentage of DoD energy use is for aircraft and ships, the increases after 2020 would not be significant in the context of overall DoD energy use, but could be in the context of the percentage increase in hydrogen consumption.

Because the amount of hydrogen required through at least 2015 is small, its use will not measurably contribute to achieving DoD goals for reducing petroleum

use during that period. The relatively few installations at which hydrogen is used would have no air emissions at the point of use. As discussed previously, the total system emissions impact will depend on the hydrogen pathway. After 2020, increased use of hydrogen could contribute substantially to reducing petroleum use, and could enable DoD operations to more easily achieve emissions consistent with local, regional, and state air quality requirements.

Using hydrogen at permanent bases and installations is not expected to have any impact on mission accomplishment.

Forward Bases and Combat Operations

Portable Power

Before 2015, the most feasible military use of fuel cells would be to provide portable power. In this role, they would replace the batteries that currently provide power for such applications as field communications equipment. This report does not address the topic of battery replacement for portable power applications. However, we recommend that hydrogen use for this purpose, and the related logistics, be thoroughly analyzed by DoD.

Stationary and Vehicle Power

After 2015, fuel cells could become a more serious option for forward-deployed stationary installations and APU applications in tactical vehicles. These APUs could operate all systems aside from propulsion of the vehicle, including space conditioning, communications, information displays, computers, and other equipment. The vehicle APUs could also provide electrical power for staging areas, field kitchens, forward control areas, communications equipment, and other requirements, displacing conventional systems powered by petroleum-derived fuels. Alternatively, skid-mounted fuel cell systems could be employed to meet electrical power requirements. Mission benefits associated with both fuel cell APUs and fixed units would be reduced noise and temperature signatures on the battlefield.

With successful development of reformer technology, hydrogen could be reformed from conventional fuels brought to the forward areas. Logistics requirements for fuel could be reduced, because fuel cells convert energy more efficiently than internal combustion engines. Without successful development of reformer technology, however, the challenge of moving hydrogen to the battlefield presents serious logistics challenges as described previously.

We do not expect hydrogen to be a viable option for either tactical vehicles or forward-deployed stationary installations before 2020. This conclusion is based on the remaining development challenges for fuel cells, juxtaposed with military requirements such as reliability and durability. The conclusion also reflects our assessment of the alternatives for getting hydrogen to the battlefield, and the

progress still needed on hydrogen production, storage, and transportation technologies.

BENEFITS AND IMPACTS

Hydrogen use by DoD has many potential benefits. Realistically, though, overcoming the barriers in terms of cost, reliability, and availability on demand will require at least another decade. While cost may not be so important, given sufficient mission benefits, overcoming the other challenges is vital for accomplishing military operations with precision, confidence, and reduced threat to personnel.

While mission benefits of hydrogen as a fuel are years away for deployed forces, DoD planners should establish a mechanism to continually assess and plan for its introduction into military operations. DoD use of petroleum and other fuels around the world represents a large investment on behalf of the nation. A small fraction of this resource applied to obtaining operational confidence in selected hydrogen energy applications could better position DoD for future decisions. During the next 10 years, more cross-service use of hydrogen energy for stationary power and vehicle fleet service, in the context of demonstration and pilot projects, would provide data to help DoD commanders and logistics managers evaluate the hydrogen alternative.

HYDROGEN USE AT DOD FACILITIES

In fiscal year 2003, the DESC purchased 153,225 kilograms of liquid hydrogen and 17,000 cubic feet of gaseous hydrogen for the DoD.[41] Liquid hydrogen was used for missile propellant, cryogenic cooling, laser firing, and independent R&D. Gaseous hydrogen was used for short-term engine testing and laser firing. The potential for expanded use of hydrogen on domestic DoD military bases is constrained by a narrow supplier base for hydrogen-powered equipment and the lack of economies of scale, which result in high costs. In addition, there is nearly universal agreement that expanded hydrogen use should be limited to those applications that provide economic benefit[42] or directly demonstrate new technologies that have clear applications to future mission requirements.

Our interviews with hydrogen proponents revealed a strong consensus that widespread use of stationary fuel cells is necessary to create better acceptance and markets for fuel cells and hydrogen. DoD has been a leader in the placement of

[41] Defense Energy Support Center, "DESC Hydrogen Management," Missile Fuels Commodity Business Unit presentation to LMI, San Antonio, TX, July 16, 2004.

[42] Phillip J. Schendler, *Costs and Benefits of Using Fuel Cells for Stationary Power Generation at Marine Logistics Base Barstow Maintenance Center*. Master's Thesis, Naval Postgraduate School, 2002. Monterey, CA, December 2002. Examines data collection and analysis needed to determine the economic return on an investment in fuel cell technologies for power generation.

over 127 stationary fuel cells for test and evaluation projects.[43,44,45] These demonstrations were carried out in the United States and overseas under various programs managed by the CERL at a cost of over $73 million since 1993.[46] These fuel cells used either hydrogen from reformed natural gas or propane, or, in the case of backup power systems, hydrogen provided from compressed cylinders. Overall availability of the larger phosphoric acid fuel cells averaged 66.2 percent through January 31, 2003, with average system efficiency of 31.6 percent.[47] Availability of the smaller proton exchange membrane fuel cells has averaged 90 percent, with average system efficiency of 24.6 percent.[48]

Stationary fuel cells at military bases within the United States would most likely continue to use hydrogen from on-site steam methane reformation until hydrogen would become widely enough available as an energy commodity that it could be competitively purchased and economically shipped. The availability of natural gas pipelines with sufficient capacity to support increased demand is critical.

It needs to be noted here that most military bases currently have interruptible natural gas contracts to permit fuel switching when natural gas shortages occur. This reduces DoD costs but would not be feasible if fuel cells are intended for primary power generation. An alternative would be to construct hydrogen storage at military bases to hold excess or purchased hydrogen for use when natural gas is not available or subject to interruption.

The logistics of hydrogen for DoD facilities overseas is little different from that envisioned domestically. If the host country has hydrogen production capacity in excess of industrial needs, hydrogen could be supplied in gaseous or liquid forms by truck, pipeline, barge, or rail. Solid-state hydrogen could be delivered by truck, barge, or rail. Hydrogen could be produced from natural gas, if available, or by electrolysis. However, as in the domestic scenario, the cost and risk of rapidly evolving technologies is high.

[43] W. R. Major and C. R. Miles, *Fuel Cell Power Systems for Navy Applications*, Naval Civil Engineering Laboratory, Port Hueneme, CA 93043, Report No. TN-1696, May 1984.

[44] M.J. Binder, W.R. Taylor, and F.H. Holcomb, "Experience with the DoD Fleet of 30 Fuel Cell Generators," U.S. Army Engineer Research and Development Center, Presented to the 2001 International Gas Research Conference (IGRC 2001), Amsterdam, The Netherlands, November 5-8, 2001.

[45] DoD Fuel Cell, ERDC/CERL Programs, online at http://www.DoDfuelcell.com/, accessed July 30, 2004.

[46] Online at http://www.DoDfuelcell.com, accessed August 20, 2004. (Note that this reported value is not inclusive of all hydrogen fuel cell activities within DoD.)

[47] Online at http://www.DoDfuelcell.com/pafc/index.php4, accessed August 20, 2004.

[48] Online at http://www.DoDfuelcell.com/res/site_performance.php4, accessed August 20, 2004.

HYDROGEN USE IN MAJOR WEAPON SYSTEMS

Within DoD there has been interest in the use of hydrogen for the propulsion of ships and aircraft.[49,50] The U.S. Coast Guard has developed a simulation of a molten carbonate fuel cell-powered electric-drive ship.[51] However, the barriers to hydrogen's use as propulsion fuel for ships and aircraft are extensive. Therefore, hydrogen use in these weapon systems is unlikely in the near-term or mid-term transition to the "hydrogen economy."[52]

It is highly unlikely that hydrogen could be used for primary propulsion on Navy ships because they would need to carry four times the current volume of fuel (if the hydrogen were liquefied), or they would need to refuel four times as often as they do now. In addition, confined spaces on Navy ships and the low ignition energy for hydrogen "could lead to an untenable situation, even in the absence of combat."[53] The situation for high-performance military aircraft is similar, where hydrogen does not appear to be a "viable fuel for the high-performance low altitude aircraft central in DoD present capability."[54]

The preceding facts argue against a rapid replacement of petroleum fuels with hydrogen for use in major combat systems. While the weight of hydrogen to deliver energy is less than JP8, the volume of hydrogen under all current and identified future technologies is significantly greater. Therefore, the number of vehicles needed to deliver energy is higher. The tonnage of fuel moved would decrease under some circumstances, but the tonnage and complexity of the production, storage, and distribution systems would assuredly increase dramatically.

We believe that DoD should encourage, but not drive, further development of large-scale hydrogen production and improvements in hydrogen distribution that promote lower hydrogen and infrastructure cost through commercial competition. DoD should begin by purchasing hydrogen wherever direct SMR or other reforming is not integrally linked directly to a fuel cell facility on base. Hydrogen storage infrastructure must then be developed in synchronization with the expansion of hydrogen use for fuel cells and fuel cell vehicles.

[49] Tim Edwards, *Ambient Hydrogen Storage Assessment for Aerospace Propulsion,* Air Force Research Laboratory, Propulsion Directorate, Wright-Patterson AFB, OH, undated document.

[50] Coffey et al., *Hydrogen as a Fuel for DoD.*

[51] Z. Karni et al., *Dynamic Simulation of a Fuel Cell-Powered Electric-Drive Ship,* U.S. Coast Guard Research and Development Center, 1082 Shennecossett Road, Groton, CT, 06340-6096, Final Report, Report No. CG-D-12-01, February 2001.

[52] Joseph J. Romm credits the phrase "hydrogen economy" to Australian electrochemist John Bockris. Joseph J. Romm, *The Hype About Hydrogen,* Island Press (Washington, Covelo, London), 2004, page 3.

[53] Coffey et al., *Hydrogen as a Fuel for DoD,* page 4.

[54] Ibid.

BATTLESPACE HYDROGEN LOGISTICS

Three physical states of hydrogen have been described: liquid, gaseous, and solid-state. The physical state of hydrogen used by DoD will fundamentally depend on the mission and design of weapons or combat systems, since fuel cells will work best where designed as part of an integrated system. These designs will likely first use gaseous hydrogen and then solid-state hydrogen carriers, if DOE research into this technology proves successful. This generalization would not apply to all systems, as we envision that modular fuel cells for power or battery replacement could have a prominent role in early hydrogen adoption by DoD. Decisions on the physical state of hydrogen needed will be a major determinant of DoD infrastructure needs and the associated hydrogen production, distribution, and storage requirements. This will in turn drive the “who, what, where, when, and how” for reforming feed stocks into hydrogen.

Deployment of hydrogen into combat equipment and combat support infrastructure (mobile electric power, batteries, and so on) offers unique opportunities to enhance stealth and reduce infrared signatures for extended periods of operation. We envision that fuel cell technologies could be a force multiplier for remote sensing and special operations forces where batteries or solar panels limit existing mission capability. Even without JP8 reformers, in the small quantities that would be required, hydrogen could be shipped in palletized compressed gas bottles or in dry solid-state materials for high-value applications. This limited use of hydrogen could be handled within the current DoD logistics system.

There is more to battlespace hydrogen logistics than the hydrogen itself. There would be fuel cells, reformers, and additional transport trucks moving hydrogen from the point of production to bulk storage, and specialized refueling trucks and systems for refueling individual equipment. This supporting infrastructure requires personnel, and maintenance and repair support. It would be necessary to return fuel cells needing repair to a depot-level installation because of the fine tolerances and clean room requirements for breakdown and reassembly. Conversion of the existing fleet of weapons will take decades, meaning that multiple fuels would be needed in the battlespace in the interim. Until the entire combat force is converted to hydrogen, petroleum logistics will need to operate in parallel with hydrogen logistics.

In the existing and currently foreseen domain of hydrogen technology and use, DoD cannot depend on commercially available hydrogen production, storage, and distribution equipment in a military conflict, for the simple reason that worldwide commercial availability of hydrogen equipment is currently very limited, compared to petroleum equipment, and not standardized. The military services would need to develop a full menu of equipment, personnel, training, maintenance, and operations and repair capability in the absence of this commercial infrastructure. At this very early stage in the development of the hydrogen economy, there is

significant risk of pursuing immature technologies for an expansive conversion of DoD to hydrogen. DoD should build on commercial industry experience.

Military forces would need to have hydrogen feed stocks (electricity and water, natural gas, biomass, coal) available in the battlespace unless progress on the reforming of logistics fuels becomes a reality. Electrolyzers and reformers of different types would need to be available to convert the available regional feedstocks to hydrogen, but without sufficient reliability and durability they could become potential logistics choke points. These are high-cost and high-value military targets, as are the specialized trucks needed to distribute the fuel. Temporary "bag farm" petroleum storage would need to be replaced with steel insulated tanks for liquid hydrogen storage or high-pressure tubes for gaseous hydrogen. This would significantly increase the weight, volume, footprint and complexity of combat support infrastructure, and would likely increase personnel requirements.

SUMMARY AND CONCLUSIONS

Development of production, storage, transportation, and distribution systems on a scale necessary to replace petroleum use with hydrogen throughout DoD is inextricably linked to successful development of light-duty fuel cell vehicles. Government and industry are evaluating many options of hydrogen use in vehicles and other potential applications. However, the DOE's hydrogen fuel cell vehicle commercialization decision is not anticipated until 2015.[55] While initial prototypes of light-duty vehicles are currently being demonstrated by auto manufacturers, small-quantity mass production of fuel cell vehicles by the auto industry is unlikely to occur before 2020.

As discussed and in view of the apparent distant horizon of fuel cell vehicle development by government and industry, it is highly unlikely that a major military shift from petroleum fuels for ground mobility and support equipment to hydrogen will be possible in the next two decades—or longer. Use of petroleum for the propulsion of ships and aircraft will likely be required for an additional two to three decades. Reliance on future developments in hydrogen technologies to reduce the petroleum logistics tail and DoD's exposure to supply disruptions would be misplaced, since over 90 percent of DoD's petroleum use is for propulsion of ships and aircraft. It is therefore imperative that DoD improve energy efficiency of existing and future combat systems operated on petroleum by implementing currently available technologies,[56] while closely monitoring and selectively utilizing worldwide hydrogen developments.

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[55] U.S. Department of Energy, *Hydrogen Posture Plan*, February 2004, page 6.

[56] A discussion of weapons systems fuel efficiency can be found in the report *More Capable Warfighting Through Reduced Fuel Burden*, The Defense Science Board Task Force on Improving Fuel Efficiency on Weapons Platforms, January 2001.

Chapter 5

Findings and Recommendations

In Chapter 1, we outlined several questions that confront DoD/DLA in responding to Congress and considering hydrogen as a DoD logistics fuel. The questions we posed were:

- Is the use of hydrogen a viable option for DoD?
- What infrastructure development would be necessary, and what timeline would be expected, to begin using hydrogen fuel in step with industry developments?
- What would be the costs and benefits of making the transition to a hydrogen fuel-based force, for both a home-based force and a deployed warfighting force?

These questions were framed to address the issues Congress directed DLA to consider in assessing the potential of hydrogen as a transportation and power generation fuel, the potential sources of hydrogen as a fuel domestically and overseas, and the potential reduction in fuel cost, logistics footprint, and air emissions during deployed military operations. On the basis of our foregoing research and discussion, we offer the following findings and responses to those questions, as well as recommendations for further action.

FINDINGS

Is the use of hydrogen a viable option for DoD?

Hydrogen as fuel may become a viable option for the Department of Defense. Hydrogen has the *potential* to be used almost anywhere, and at almost any time. As described in Chapter 4, hydrogen could enable enhanced capabilities in accomplishing the DoD mission. Combining hydrogen with the right systems and technologies offers the potential for improving battlefield effectiveness through:

- Near silent operations
- Significantly reduced infrared exposure
- Longer power availability than with batteries
- Lighter weight than batteries
- Extraction of hydrogen from suitable feedstocks nearly anywhere at any time.

In addition, the use of hydrogen in fuel cells offers the opportunity to enhance air quality and reduce production of greenhouse gases. This attribute depends entirely on the choice of method for producing the hydrogen. Clearly air emissions can be reduced at the end use point of the "energy chain," but the total system reduction will depend on the renewable and efficient generation of hydrogen. It is not feasible to ascribe specific values to these benefits until future technology developments and production decisions have been made.

The most likely near-term (2005–2015) to mid-term (2015–2035) opportunities for hydrogen and fuel cell introduction are on a small scale. Current efforts related to using fuel cell technology for battery replacement may offer some force multiplier advantages and do not necessarily require the development of dedicated logistics/supply chains. These applications primarily would be to replace current batteries used in handheld and portable devices. Although detailed research on this particular fuel cell application was not part of this logistics fuel study, the developments along this path and the resultant logistics implications could be monitored and incorporated into future efforts. Obviously, if the fuel cell becomes a successful replacement for standard batteries, then there might exist a natural synergy and complementary strategy for expanding the fielding of hydrogen as a logistics fuel.

The next most likely path for introduction of hydrogen in DoD is in stationary, non-combat, permanent base/garrison applications. The transition to hydrogen appears at this time more feasible for fixed facilities than for vehicles. Additionally, using hydrogen in domestic installations is the most likely first step before introducing it overseas. Assuming that current efforts continue to prove viable and successful, we could see expansion of the technology, and infrastructure to support this expansion, in the mid-term. This would be linked to the state and progress of commercialization of hydrogen within the domestic economy and the resultant economies and capabilities.

A departure from this domestic, fixed-base pathway could be the potential introduction of hydrogen/fuel cell technology in expeditionary operations that require mobile power generation, auxiliary power, and other related capabilities. If some of the remaining technology and storage issues could be resolved, the operational benefits we described earlier would warrant serious consideration for wider hydrogen introduction. Current efforts to develop, field and test mobile power generators and auxiliary power units offer opportunities to harness some of the stealth and efficiency benefits of the technology. However, DoD must confront survivability and supportability issues in that environment before an "operational" decision could be made. This is why we believe this particular application is not feasible on a broad scale until the mid-term.

One must take a much longer perspective before hydrogen can be considered viable for use in DoD's major mobile weapon systems. Current studies and efforts seem to rule out consideration of hydrogen as a viable fuel for ship and aircraft propulsion. Given the acquisition cycles and life expectancy of major weapon

systems, it might take several decades before hydrogen could even begin to replace fossil fuel as a primary energy source for these applications. The conversion of major weapon systems would be premature and is unlikely, given the current status of hydrogen and fuel cell development. Furthermore, until some additional breakthroughs occur in hydrogen technology, particularly storage, there will be no basis for introducing the technology in emerging weapon systems. Hence, it is our finding that the introduction of hydrogen in major weapon systems will occur only after a transition throughout the rest of DoD.

Based on this long-term (2035-future) consideration for major weapon systems, DoD will continue to rely on petroleum for the foreseeable future (the next 30–40 years). The predominant use of fossil fuels by the Air Force and Navy is for mobility purposes and would not be replaceable in the near- or mid-term. In addition to this barrier to conversion, the following factors also impede introduction of hydrogen on a large scale:

- Petroleum today is the most cost-effective and operationally capable fuel.
- The supporting infrastructure for petroleum is established and available, both domestically and globally.
- Petroleum standards are well established and adhered to on a wide scale.

Only with the passage of time and further technological development will this equilibrium change and the stage be set for wider adoption of hydrogen as a primary “logistics fuel.”

What infrastructure development would be necessary, and what timeline would be expected, to begin using hydrogen fuel in step with industry developments?

Making a transition to a hydrogen energy base will be costly and time-consuming. The construction and evolution of the hydrocarbon- and electrical-based fuel distribution systems have taken decades—close to a century—and billions of dollars. Even on a macro scale, one would have to contemplate decades and billions of dollars, as well, to develop a true hydrogen-based economy and the potential for replacing these existing infrastructures. Much of the size, design, complexity, and cost of the new infrastructure cannot be determined until several developments and decisions take place regarding the production, movement, and storage of hydrogen. Fundamental issues such as the predominant production method and form for shipment and storage must be resolved in order to guide decisions on effective and efficient infrastructure investment.

As discussed in Chapter 2, the federal government and DoD comprise a very small percentage of domestic energy consumption (even much less on a global scale). Consequently, as with the current petroleum and electricity industries, it is not the public sector but the energy industry that will define and build the

infrastructure necessary to move toward a hydrogen economy. As is true with so many technologies, the business community and private industry will lead the way with investment and research, determining the requirements for infrastructure investment, and defining standards and expectations. If DoD were to make this decision itself, it would face the risk of selecting a technology that is not widely used or supported, or even swimming against what emerges as mainstream hydrogen use. Therefore, DoD cannot expect to use significantly larger volumes of hydrogen as a fuel—that is, 10 to 20 times current demand—for some time.

DOE has projected a target of 2015 for a commercialization decision for the use of hydrogen in production on-highway vehicles. This basically anticipates that the next decade will be spent in the research and development of some systems and technology, as well as their preliminary deployment. Even after that "decision," the actual conversion could take decades. The pace of the conversion will be entirely predicated on economic, political, and environmental factors coupled with the technology and operational capabilities. Current DoD planning underway (POM 06-11) carries out budget planning to 2011. Therefore, DoD has at least 4 years to continue to monitor technological and developmental progress before addressing the potential investment in critical infrastructure. The POM 10-15 cycle would be the earliest point to begin more detailed assessment of infrastructure requirements and the funding insertion necessary for introducing hydrogen. Similar to current investment considerations for petroleum commodities and infrastructure, this planning activity could be concentrated within DLA/DESC in support of all services.

This timeline could be influenced by the emergence of almost any disruptive change. Such change, in this context, might be a faster than expected reduction in the availability of conventional petroleum, a significantly increased concern for the emissions and resulting impacts of greenhouse gases, technological leaps in hydrogen production and storage technology, significant changes in the costs (increase or decrease) of petroleum, some catastrophic event, or other similar occurrences. Any of these, or a combination of several, could influence the timeline currently projected for establishment of the hydrogen infrastructure.

What would be the costs and benefits of making the transition to a hydrogen fuel-based force, for both a home-based force and a deployed warfighting force?

Throughout the report we have articulated several of the costs and benefits of using hydrogen as an energy carrier. The following are among the current costs and risks to DoD:

- The infrastructure for producing, distributing, and storing hydrogen carries a huge potential capital cost. This discussion excludes the cost of establishing the primary core technology itself. As we have discussed, DoD is a consumer of energy and will not be burdened with creating the

entire infrastructure, but it will be responsible for bringing the energy supply onto the base or into the field. Because there is still work to be done with respect to distributed or centralized production, some of the infrastructure decisions cannot be made yet.

- Furthermore, in the deployed environment, some amount of overland transportation of hydrogen might be anticipated. As explained in the previous chapter, the resulting logistics footprint could in fact grow as a consequence of hydrogen's "volumetric penalty." Mitigating this cost and its adverse impact on the logistics footprint is a crucial problem that must be addressed through a combination of technology and logistics refinements.

- Perhaps the biggest cost (risk) to be managed would be the introduction of new or unproven technology on the battlefield. Proper testing and evaluation under all potential scenarios and environments would be necessary.

We previously highlighted some of the potential benefits for military forces equipped with hydrogen and fuel cell technology: stealth, silence, and efficiency. If some of the remaining technical and logistical challenges can be solved, then this technology could be a true force multiplier. Not only might it offer operational advantages, but also the production methods may promote greater energy diversity for support of the operating force, both domestically and abroad. Having several different methods to produce hydrogen—coupled with different options for potential feed stocks—could conceivably enhance support to the warfighter in even austere environments. Hydrogen exists in several different forms, which may offer improvements in fuel availability and, ultimately, supportability.

As previously discussed, the potential for environmental improvement exists, because hydrogen fuel cells will enable zero emissions, at the point of use, for both distributed power generation and mobile power applications. The overall environmental impacts of hydrogen use are unknown at this time, however, since the sources, production, storage, and distribution of hydrogen are subject to many variables. The "total fuel system" environmental impacts will be a function of how hydrogen is generated and transported.

RECOMMENDATIONS

On the basis of our research and our findings, we offer the following recommendations:

Develop and Manage a DoD Strategy and Roadmap for the Introduction of Hydrogen

Although the military services (and their subordinate organizations) are studying and considering the use of hydrogen and fuel cell technology, it appears to us that this current activity is not a coordinated and holistic consideration of all elements

that would be impacted by the emergence of a hydrogen economy. Much activity has been occurring in the laboratory and the field that should be communicated and discussed among all the stakeholders in this initiative. In this regard, DoD should specifically accomplish the following:

- Establish an oversight structure in DoD to monitor the hydrogen program. This could begin as stronger collaboration at this point, followed by more formal program management over the next few POM cycles. This structure must include subject matter experts and leaders from all of the affected communities—installations, logistics, engineering, operations, safety, and others.

- Develop a comprehensive, integrated strategy and plan for the appropriate use of hydrogen, and the acquisition of the hydrogen required to meet DoD's demands. A process for updating the plan, to reflect technology advances and commercial practice, should also be defined and implemented through the oversight structure.

- Commence financial planning and programming, in anticipation of increasing demands for hydrogen within DoD, not later than POM 10-15. If the use of hydrogen is expected to replace and be managed similar to fossil fuels, then DLA/DESC might be the appropriate activity to plan and program for that infrastructure investment (similar to Class III bulk petroleum today).

Continue to Engage Industry and Government Stakeholders

Several DoD organizations or activities have engaged with industry and other government agencies to support and perform hydrogen and fuel cell research. Although we believe DoD would benefit from exerting greater direction over this type of activity, the fact is that this type of engagement should continue and expand as situations and developments warrant. Therefore, we recommend the following:

- The Department of Defense, and its individual services, should keep well informed of, and involved in, hydrogen-related developments.

- DoD should develop, continue, and expand partnerships with other federal and local agencies, and the commercial sector. For instance, the California Air Resources Board expressed its desire to work with DoD to gain operational experience and confidence in using hydrogen fuel. Many such opportunities and roles should be investigated, especially those involving the development of standards and considerations that may affect the infrastructure and commodity use of hydrogen.

Evaluate Weapon System Implications

Although the direct implications of the introduction of hydrogen may be several years (if not decades) away, some near-term preparations and actions related to weapon system acquisition are germane. DoD's actions should include the following:

- Ensure consideration of the logistics and costs of energy in the acquisition cycle. As the Defense Science Board discovered and reported in its study on the fuel burden, the logistics cost and footprint on the battlefield are quite significant. Considering fuel-related concerns and energy efficiencies early in the acquisition cycle can reduce future costs and supportability issues. Detailed guidance should be developed regarding the consideration of fuel efficiency and energy options for future weapon systems. This will help ensure the timely and effective incorporation of hydrogen technology.

- Look for some trials and opportunities in the near-term (the next 10 years). Research and explore applications offering the greatest potential for near-term introduction of hydrogen within DoD, and analyze trials in detail. These applications might include low-power distributed generation (100 kW and below), portable power, as well as battery replacement.

Appendix

Abbreviations

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
APU	auxiliary power unit
BRAC	base realignment and closure
CARB	California Air Resources Board
CBU	commodity business unit
CERL	Construction Engineering Research Laboratory
CONUS	Continental United States
COTR	Contracting Officer's Technical Representative
COTS	commercial off-the-shelf
DARPA	Defense Advanced Research Projects Agency
DESC	Defense Energy Support Center
DESC-M	Defense Energy Support Center Missile Fuels
DG	Distributed Generation
DLA	Defense Logistics Agency
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
ERDC	Engineer Research and Development Center
FCTEC	Fuel Cell Test and Evaluation Center
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HFCIT	Hydrogen, Fuel Cells and Infrastructure Technologies
HNEI	Hawaii Natural Energy Institute
IEA	International Energy Agency
IPHE	International Partnership for the Hydrogen Economy
ISO	International Standards Organization
JSF	Joint Strike Fighter

KWH	Kilowatt Hour
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MCFC	Molten Carbonate Fuel Cell
MTBF	Mean Time Between Failures
NAC	National Automotive Center
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NECPA	National Energy Conservation Policy Act
NRC	National Research Council
NREL	National Renewable Energy Laboratory
OCONUS	Outside Continental United States
OIF	Operation Iraqi Freedom
ONR	Office of Naval Research
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
PNGV	Partnership for a New Generation Of Vehicles
POM	Program Objective Memorandum
R&D	Research and Development
RD&D	Research, Development, and Demonstration
SCAQMD	South Coast Air Quality Management District
SECA	Solid State Energy Conversion Alliance
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
USAF	United States Air Force

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(MM-YYYY)* 11-2004	2. REPORT TYPE Final (Revision 1)	3. DATES COVERED *(From - To)*
4. TITLE AND SUBTITLE Potential Use of Hydrogen as a Defense Logistics Fuel Revision 1		5a. CONTRACT NUMBER GS-00F-0026M
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Funk, Stuart; Author Oh, Sonny; Author Powell, Lisa; Author McConahy, Marc (Vista); Author Haberman, David (IF); Author Gross, Tom (IF); Author		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) LMI 2000 Corporate Ridge McLean, VA 22102-7805		8. PERFORMING ORGANIZATION REPORT NUMBER LMI-DES41M1 Revision 1
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) DESC-BP (Pamela Serino) Defense Energy Support Center 8725 John J. Kingman Road Fort Belvoir, VA 22060-6222		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
A. Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report presents results of analysis of hydrogen as potential fuel for the Department of Defense as requested by the Congress. The study concluded that although there may be some near and mid-term opportunities to employ this evolving technology, it would be 30+ years before significant weapon system impacts would be noticed. Furthermore, the study concluded that the hydrogen implementation timing and infrastructure investment will be heavily influenced by the commercial energy industry. The costs and benefits of making a hydrogen transition are difficult to measure with any degree of certainty given the relative immaturity in fielding the technology. The study concluded with recommendations to develop a DoD strategy and roadmap for hydrogen introduction, broaden partnering and participation in hydrogen forums and review DoD acquisition process to specifically address energy demands in future systems.

15. SUBJECT TERMS
Hydrogen; Defense Fuel

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Nancy E. Handy
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED	Unclassified Unlimited	60	19b. TELEPHONE NUMBER *(include area code)* 703-917-7249